New Directions for Light Dark Matter

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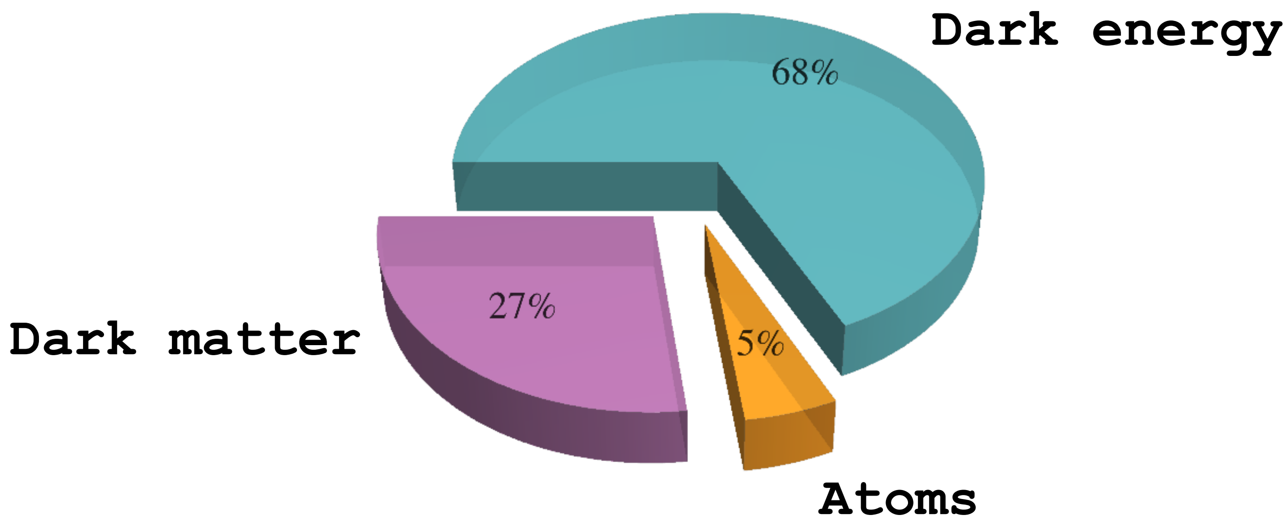
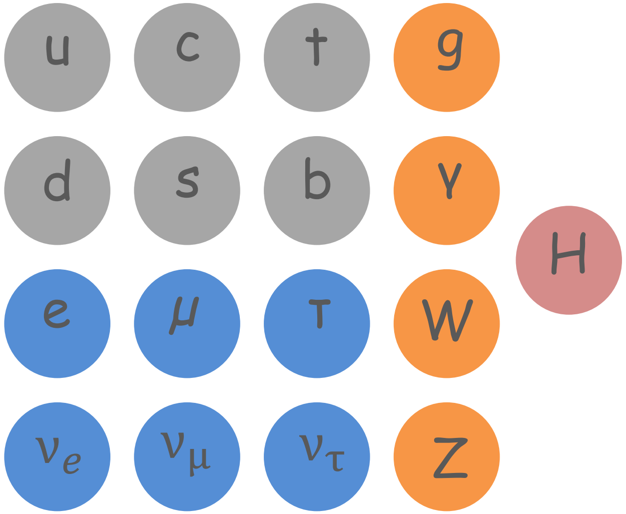
Outline

- Why?
- Theory
- Experiment

Why?

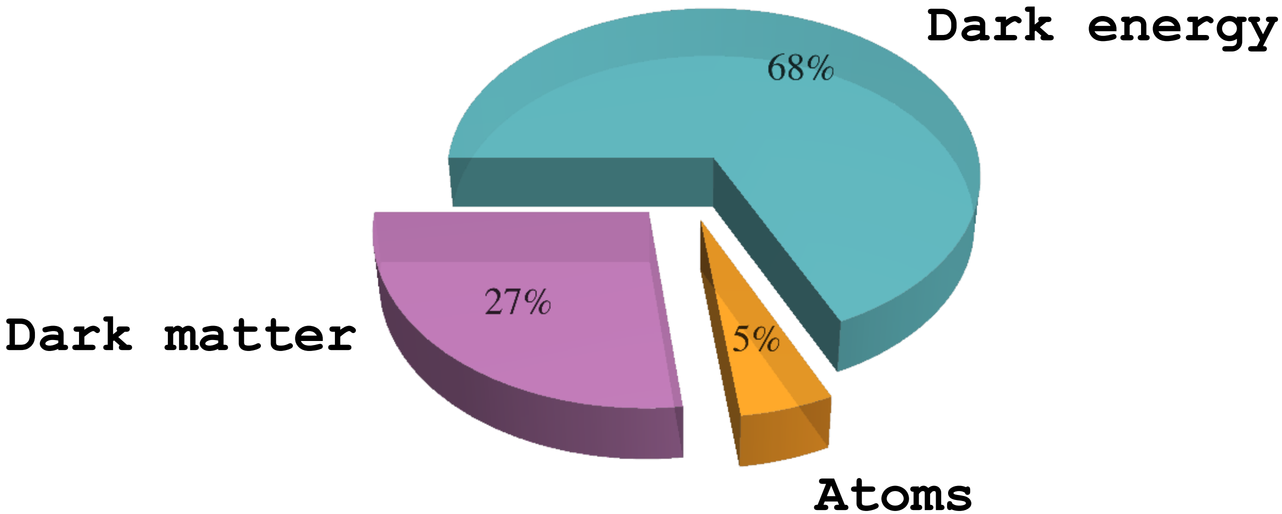
The Universe is Dark

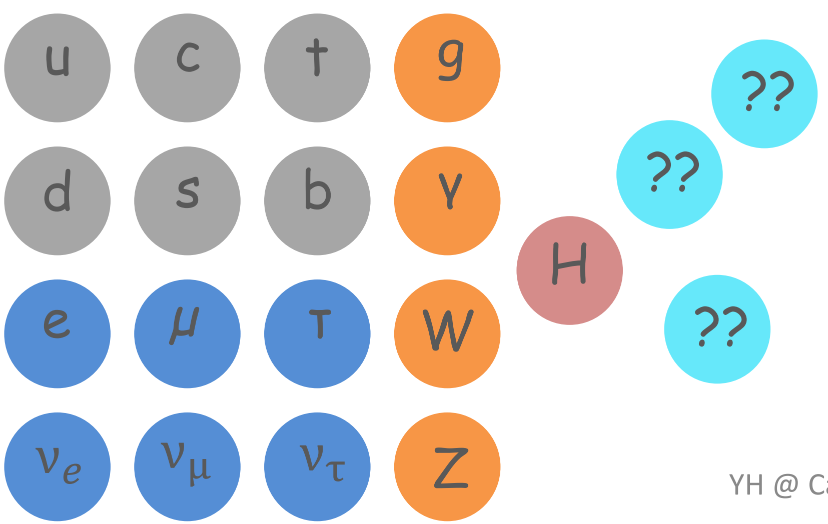




No suitable candidate within the Standard Model of particle physics

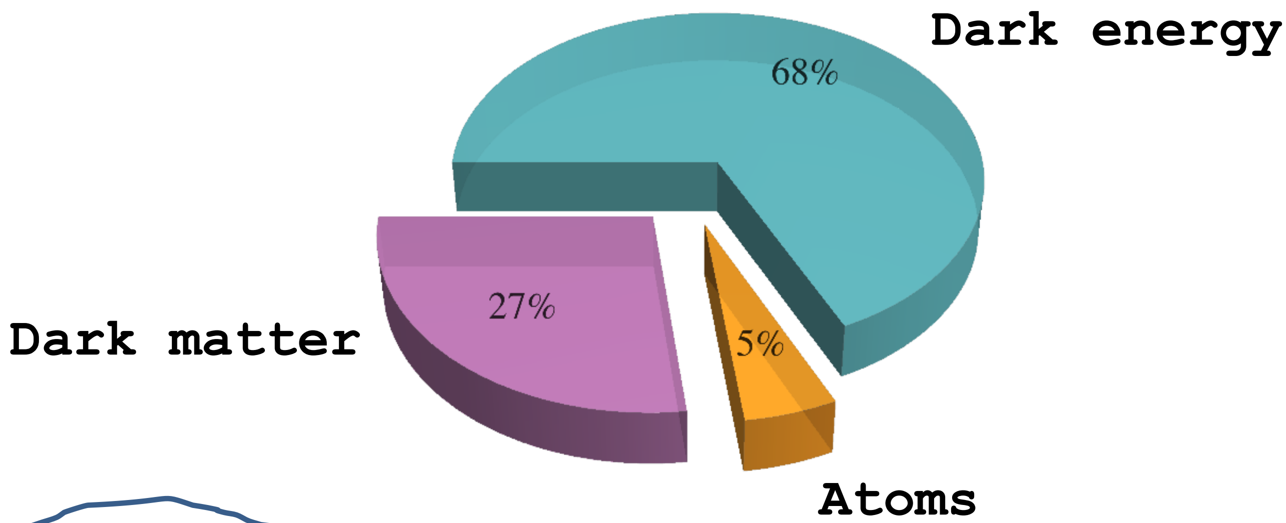
The Universe is Dark

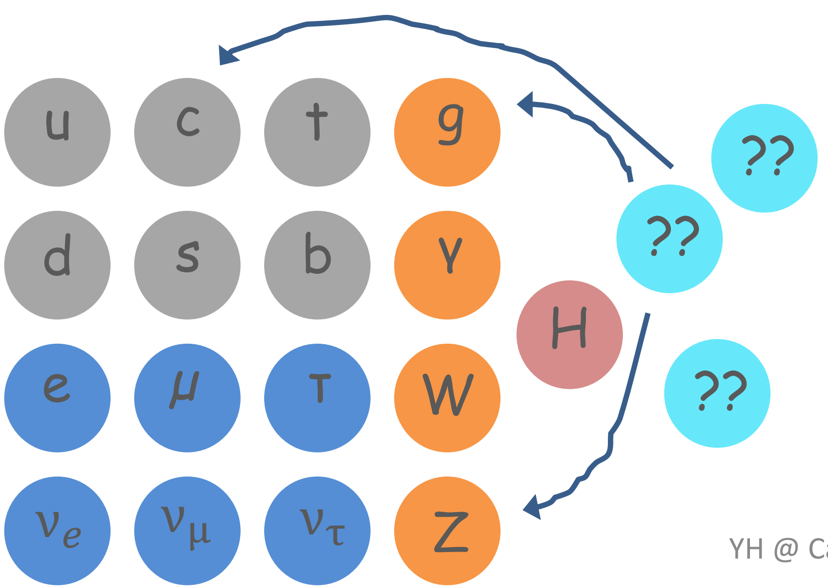




Must be at least one
new particle existing today

The Universe is Dark





What is it?
How does it interact?

What do we know?

- Dark matter has 5 times the mass density of baryons
- Massive (m=???)
- Can’t interact too strongly with QED and QCD
- Doesn’t interact too strongly with itself

Past 40 years

WIMP, glorious WIMP*

*Also axions, of course also axions :-)

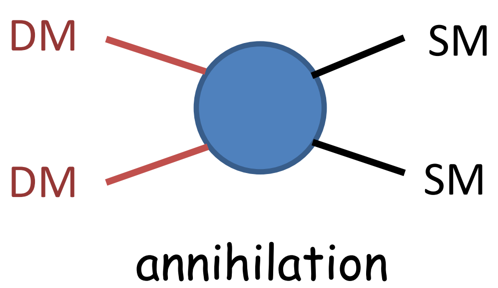
Past 40 years

Correct thermal relic abundance:

$$m_{\rm DM} \sim \alpha \times 30 \text{ TeV}$$

For weak coupling, weak scale emerges.

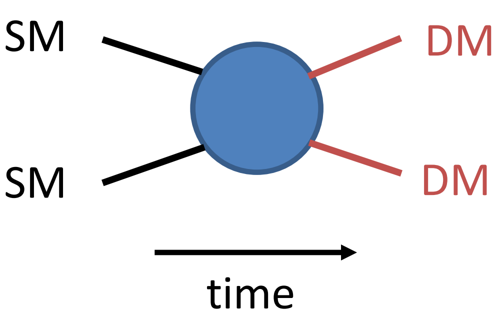
"Weakly Interacting Massive Particle (WIMP)"



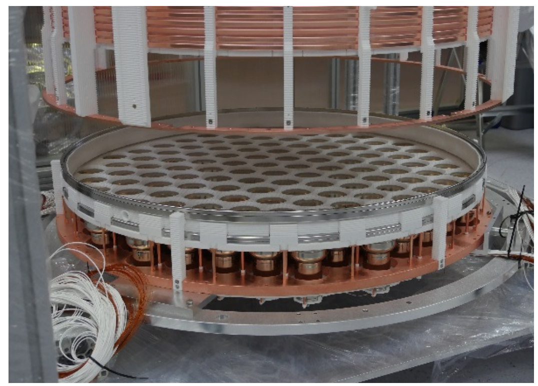
$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

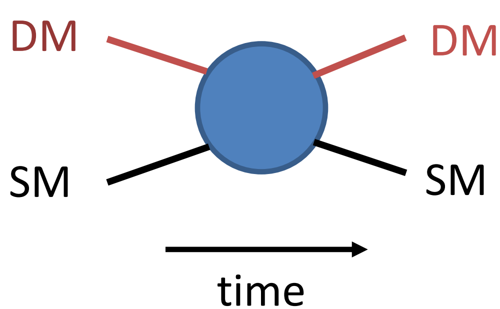
Searching for WIMPs

Direct production

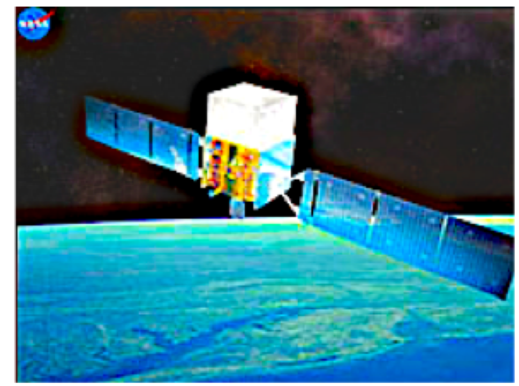


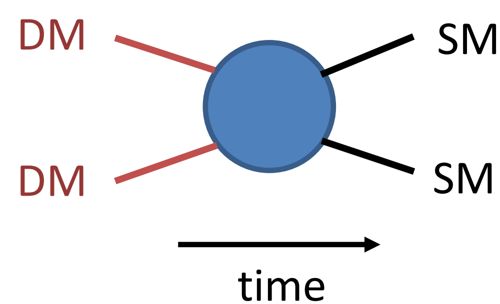
Direct detection



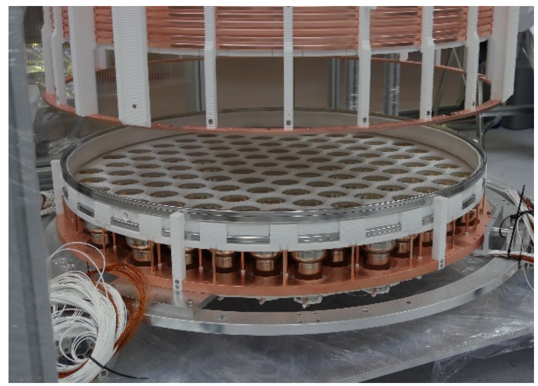
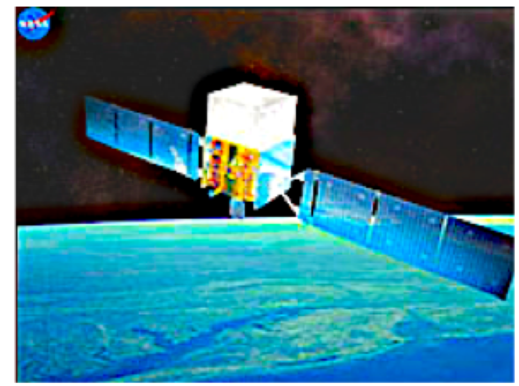


Indirect detection





Searching for WIMPs

Direct production	Direct detection	Indirect detection
		

Experiments getting increasingly sensitive

Haven't yet detected dark matter

Been searching…

Dominant paradigm is being challenged.

Sociology

Dominant paradigm is being challenged.

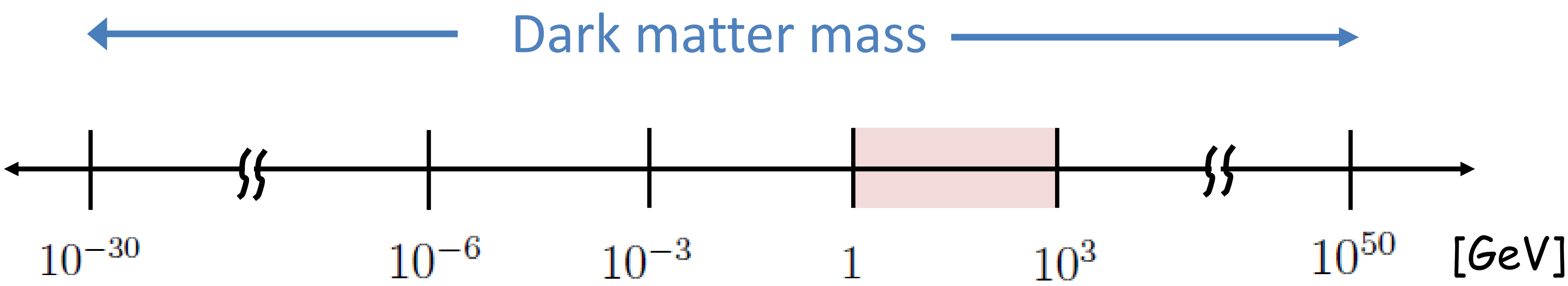
- Big puzzles
- Great if a solution gives an option for dark matter candidate
- Big ideas: Supersymmetry, extra dimensions…

⇒

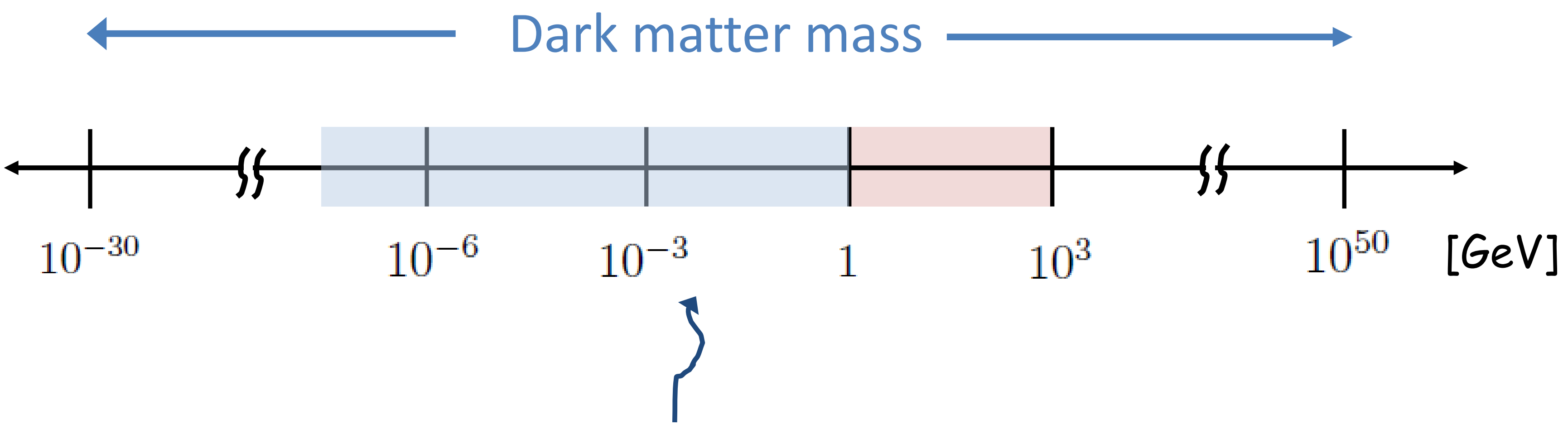
- Dark matter exists
- Explain on its own
- Perhaps decoupled from other puzzles
- Think outside the WIMP box

theoretically & experimentally

Beyond the WIMP



Beyond the WIMP



Lots of activity in recent years:

Theory & Experiment

Theory

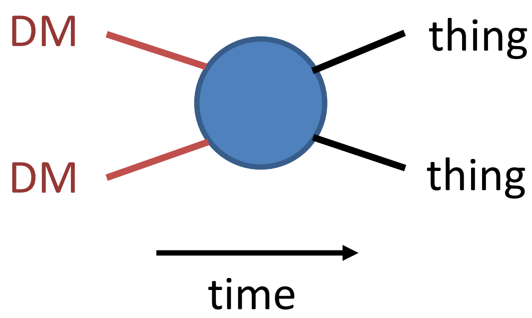
New Theory Ideas

- ……
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [Kaplan, Luty, Zurek, 2009]
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009]
- SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014; **YH**, Kuflik, Murayama, Volansky, Wacker, 2015]
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015]
- Co-decaying dark matter [Dror, Kuflik, Ng, 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- ……

… Are abundant

By no means a comprehensive list

Ex. #1: Weakly coupled 2→ 2

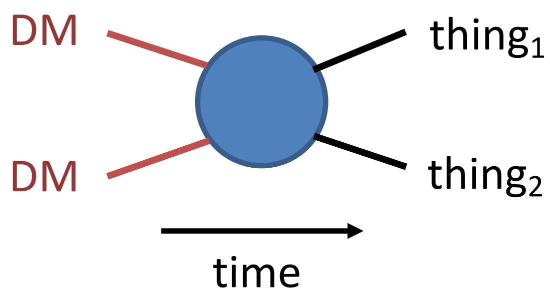


$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \ll 1$$

$$m_{\rm DM} \sim \alpha \times 30 \ {\rm TeV}$$

[Pospelov, Ritz, Voloshin 2007;
Feng, Kumar 2008]

Ex. #2: Forbidden Channels



$$2m_{\rm DM} < m_{{\rm thing}_1} + m_{{\rm thing}_2}$$

$$m_{\rm DM} \sim \alpha \times (30\ {\rm TeV}) \times e^{-x_F \Delta}$$

freezeout temp'

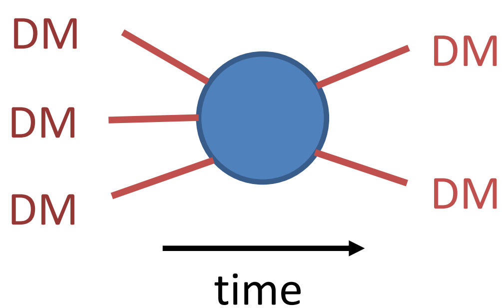
mass difference

Forbidden @ T=0;
Boltzmann suppressed @ finite T

[Griest, Seckel, 1991; D'Agnolo, Ruderman, 2015]

Ex. #3: SIMPs

What if dark matter mostly interacted with itself?



3 → 2 self-annihilations

$$\langle \sigma v^2 \rangle_{3\to 2} \equiv \frac{\alpha^3}{m_{\rm DM}^5}$$

$$m_{\rm DM} \sim \alpha \times 100\ {\rm MeV}$$

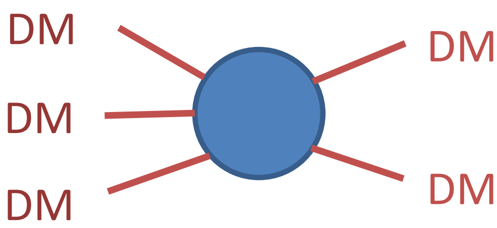
For strong coupling, the strong scale emerges.

SIMP = Strongly (self) Interacting Massive Particle

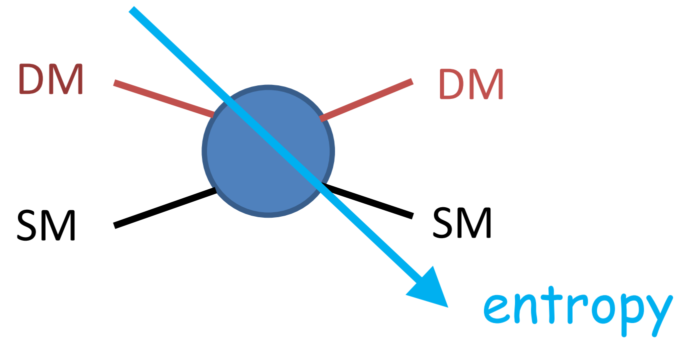
[Carlson, Hall, Machacek, 1992;
YH, Kuflik, Volansky, Wacker, 2014]

Ex. #3: SIMPs

Pumps heat into the system: need to shed the heat



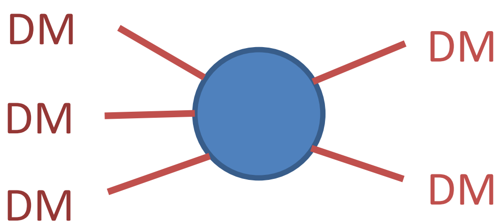
3 → 2 self-annihilations



thermalize with
light SM species
(active during freeze-out)

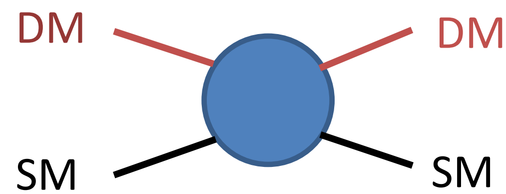
[**YH**, Kuflik, Volansky, Wacker, 2014]

Ex. #3: SIMPs



decouples 1^{st}

Determines
DM relic density

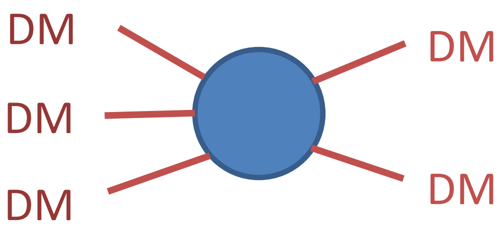


decouples 2^{nd}

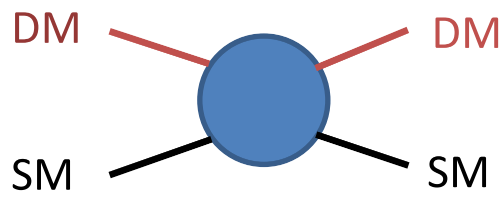
What if the order was reversed?

Ex. #4: ELDERs

ELastically DEcoupling Relic (ELDER)



decouples 2nd



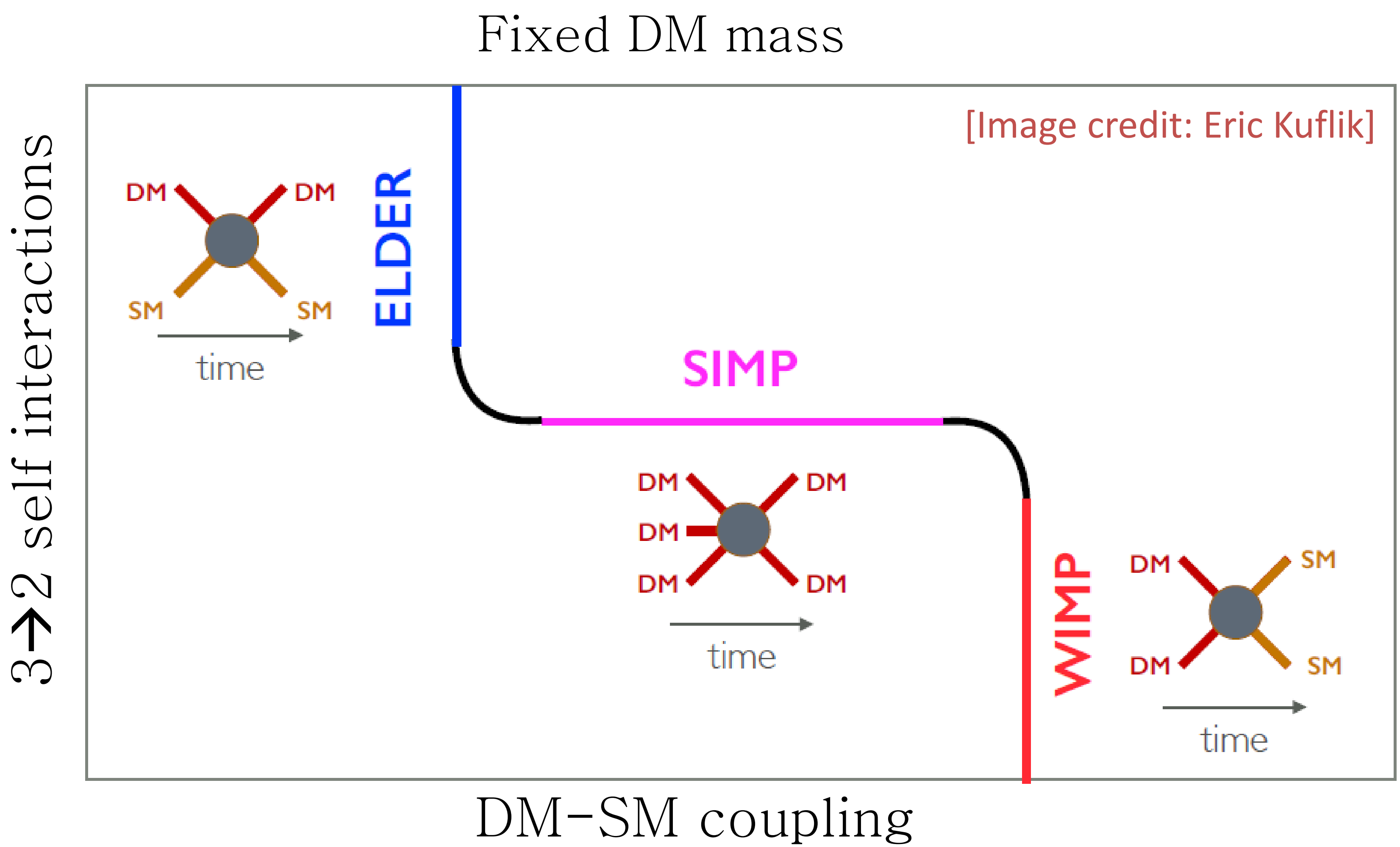
decouples 1st

Determines
DM relic density

$$\Omega_{\rm DM} \propto e^{-\langle \sigma v \rangle_{\rm el} \#}$$

[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]

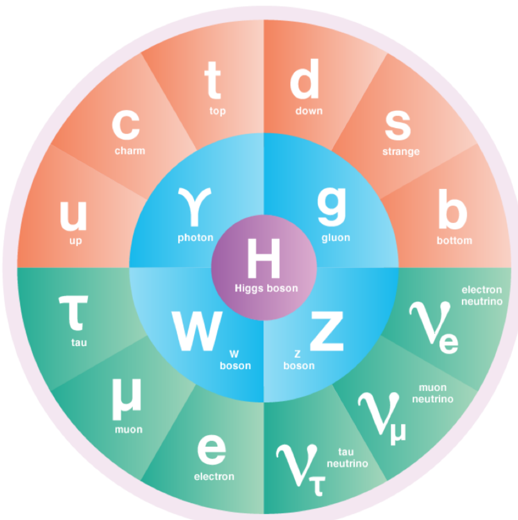
WIMP/SIMP/ELDER



Generic.

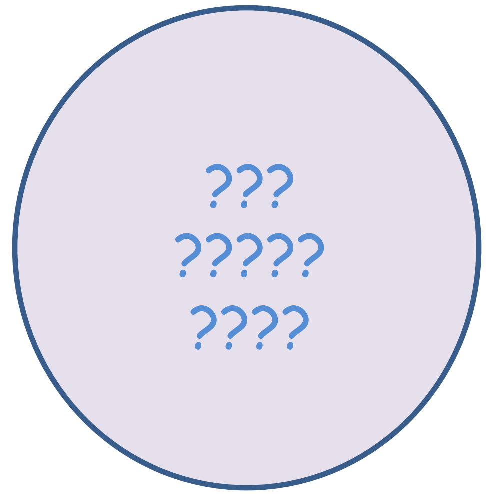
Dark Sectors

Visible sector



Zoo of particles
w/structure
$SU(3)_c x\ SU(2)_L\ x\ U(1)_Y$

Dark sector



Why not in the
dark sector too?
New gauge symmetries?

Dark Sectors

Think SM!

Dark matter from strongly coupled gauge theories

E.g. $SU(3)_{dark} \times U(1)_{dark}$

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$

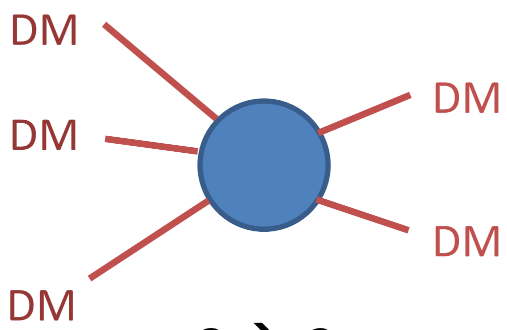
Kinetically mixed hidden photon (V)

QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

E.g. SIMPs

Think QCD!



3→ 2

QCD has 5-point interactions! $K^+K^- \rightarrow \pi^+\pi^0\pi^-$

WZW term

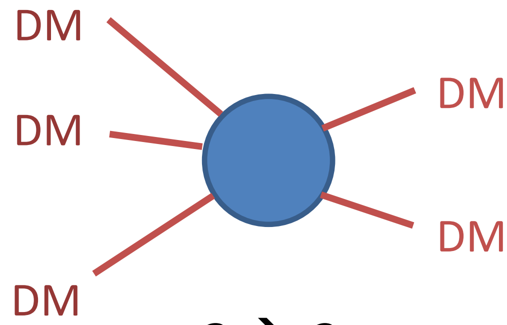
If calculate the rate, find that is just right for SIMPs with mass ~ few hundred MeV

[**YH**, Kuflik, Murayama, Volansky, Wacker, 2015]

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



3→ 2

$$\mathcal{L}_{\rm WZW} = \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$$

pion decay constant

WZW term

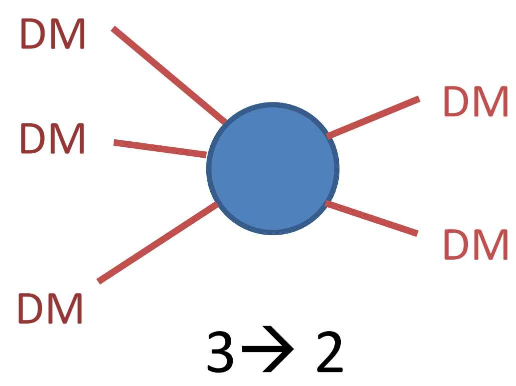
[Wess and Zumino, 1971
Witten x 2, 1983]

[**YH**, Kuflik, Murayama, Volansky, Wacker, 2015]

E.g. SIMPs

Think QCD!

$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$



Stable dark matter = dark pions

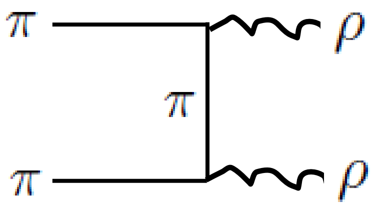
mass ~ few hundred MeV

Non-exotic!

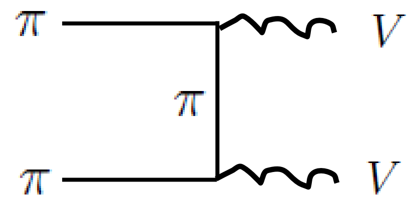
3→ 2 dark glueballs:
Carelson, Hall, Machacek, 1992; Soni, Zhang, 2016; Forestell, Morrissey, Sigurdson, 2017

[**YH**, Kuflik, Murayama, Volansky, Wacker, 2015]

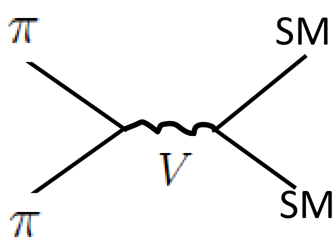
E.g. 2→2



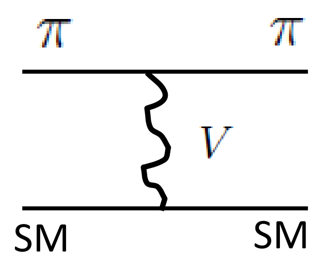
forbidden annihilations



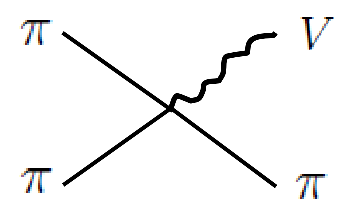
2→2 annihilations



2→ 2 annihilations



elastic scattering

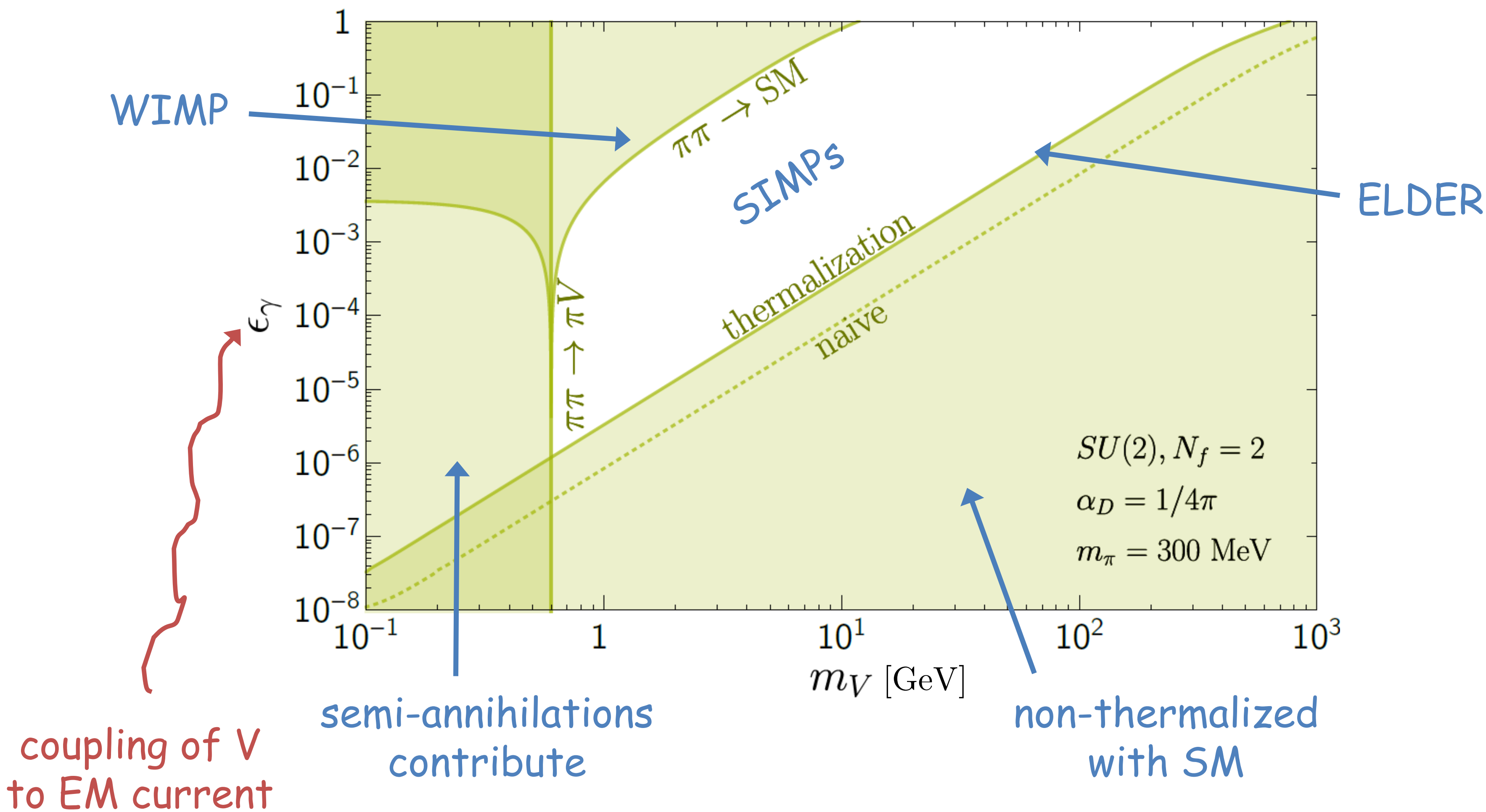


semi-annihilations

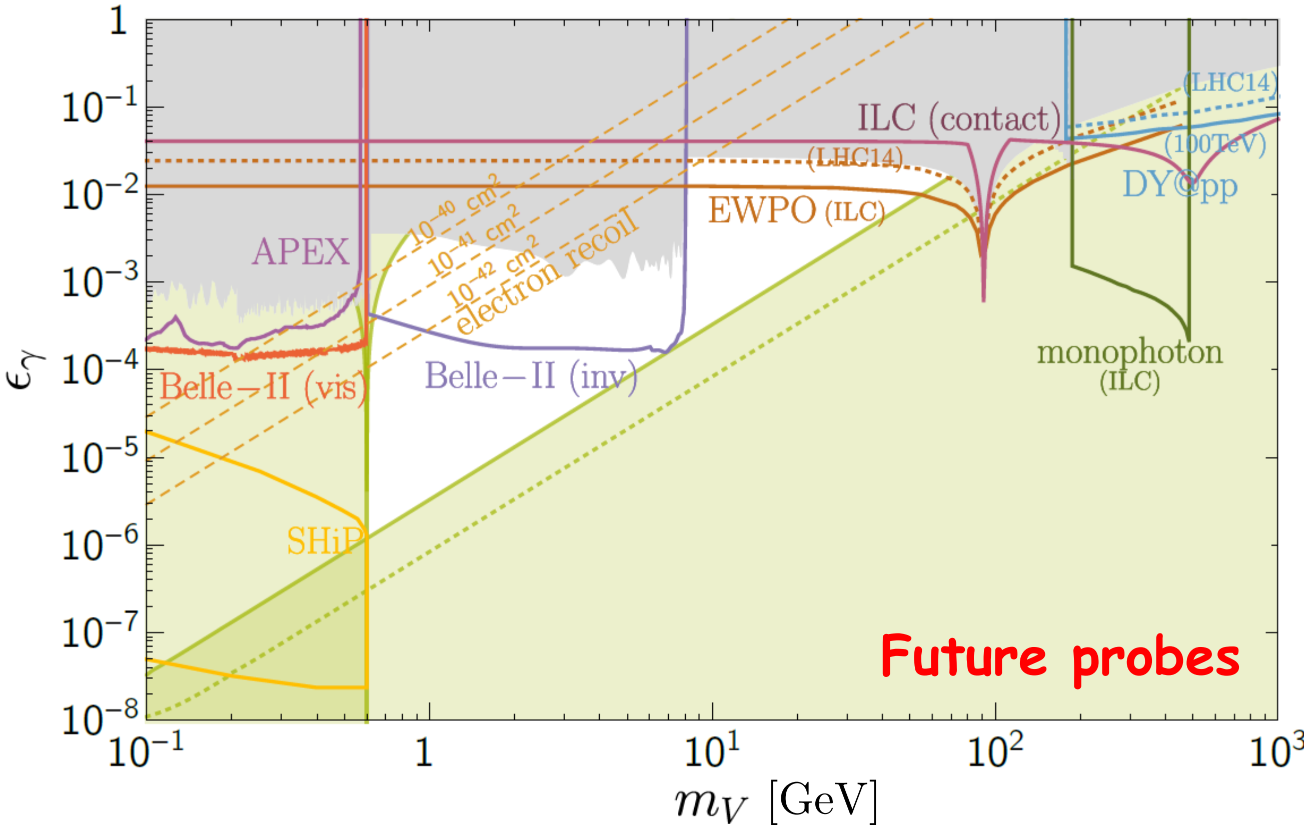
[Lee, Seo, 2015; **YH**, Kuflik, Murayama, 2016; Harigaya, Nomura, 2016; Berlin, Blinov, Gori, Schuster, Toro, 2018; ….]

Predictive.

Kinetically Mixed U(1)



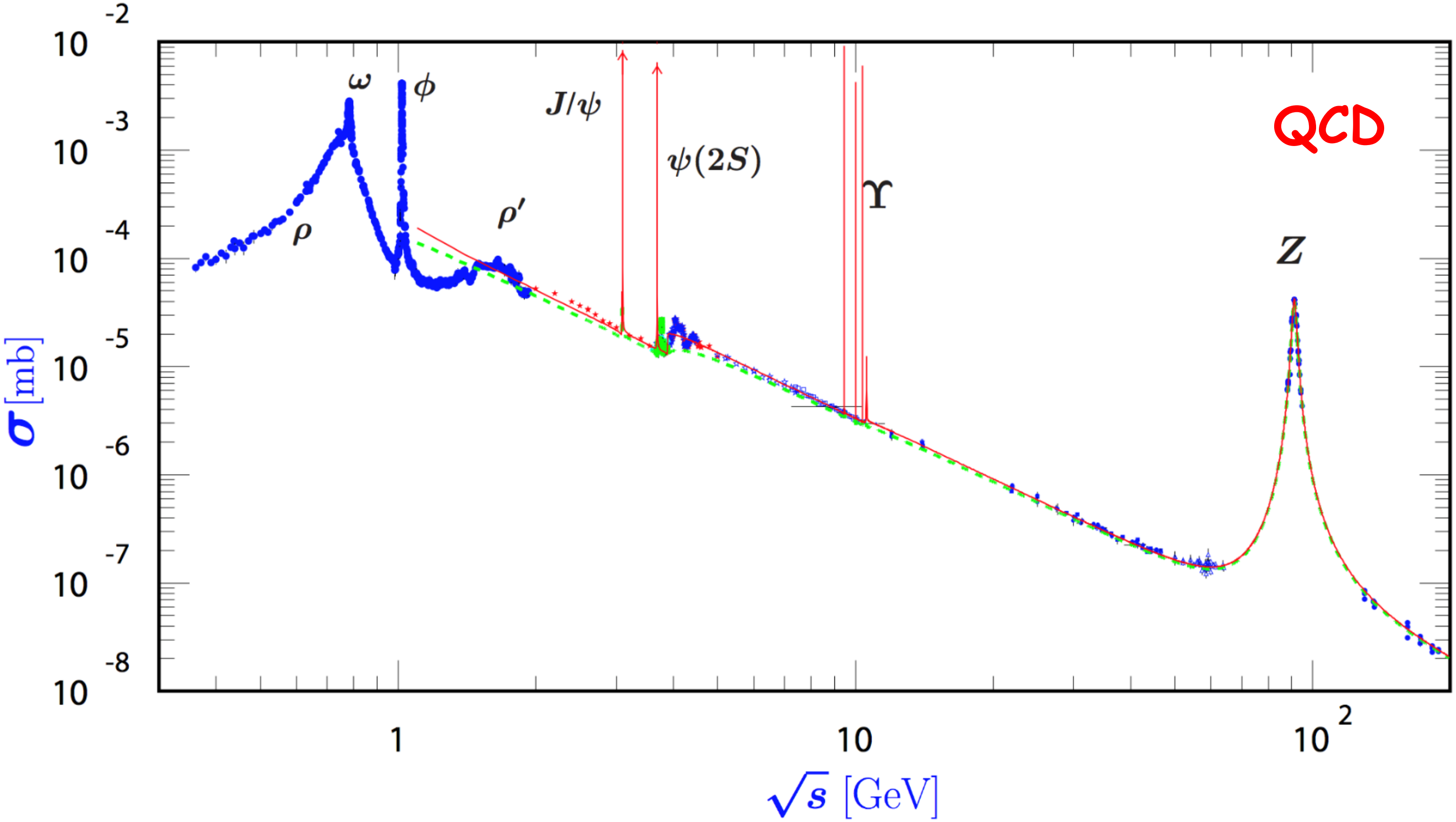
Kinetically Mixed U(1)



[Plot: **YH**, Kuflik, Murayama, 2016]

Dark Spectroscopy

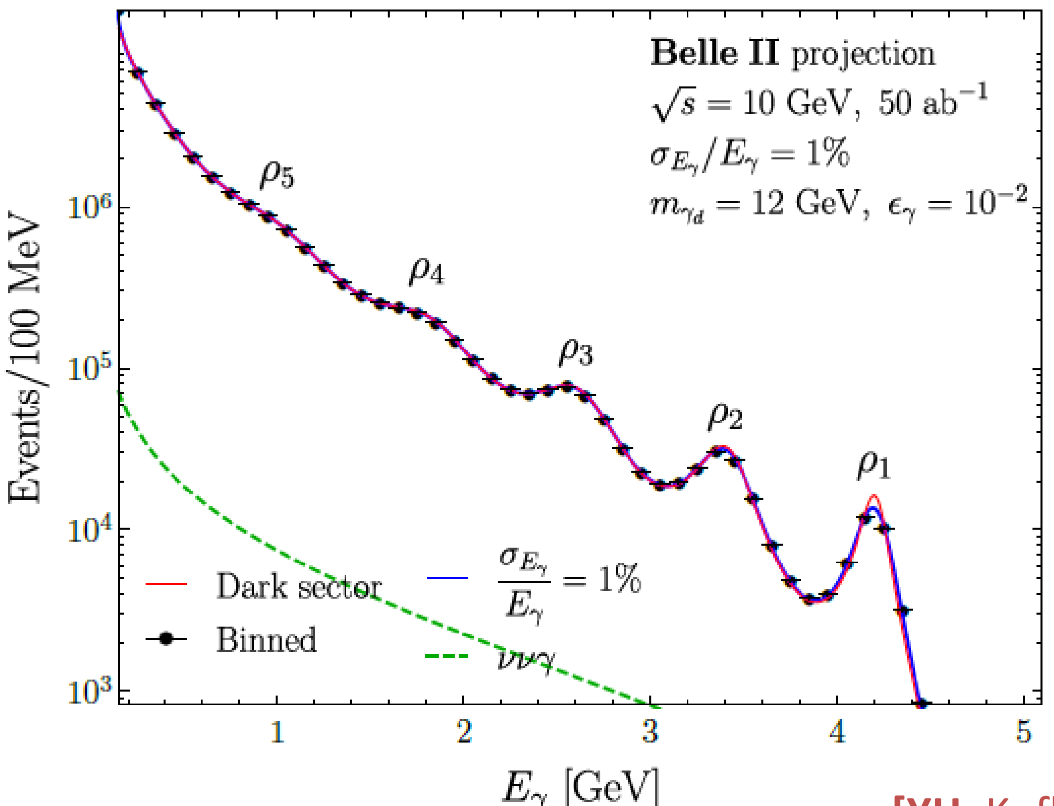
$e^+e^- \to \mathrm{resonances}$: center of mass energy traces the QCD resonance structure

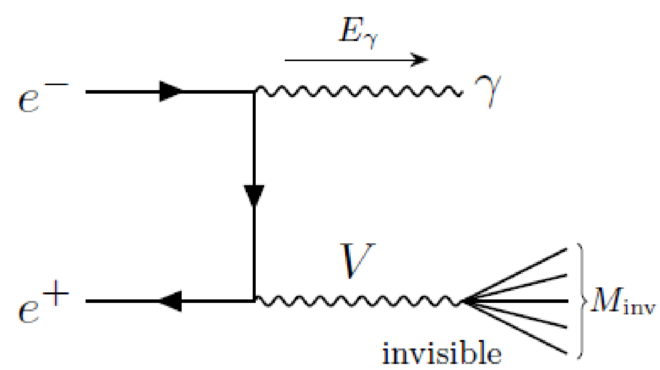


Dark Spectroscopy

$$e^+e^- \to \gamma + \text{inv}:$$

Mono-photon traces the resonance structure of the dark sector





$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$

[YH, Kuflik and Murayama, 2016 & 2017]

Experiment

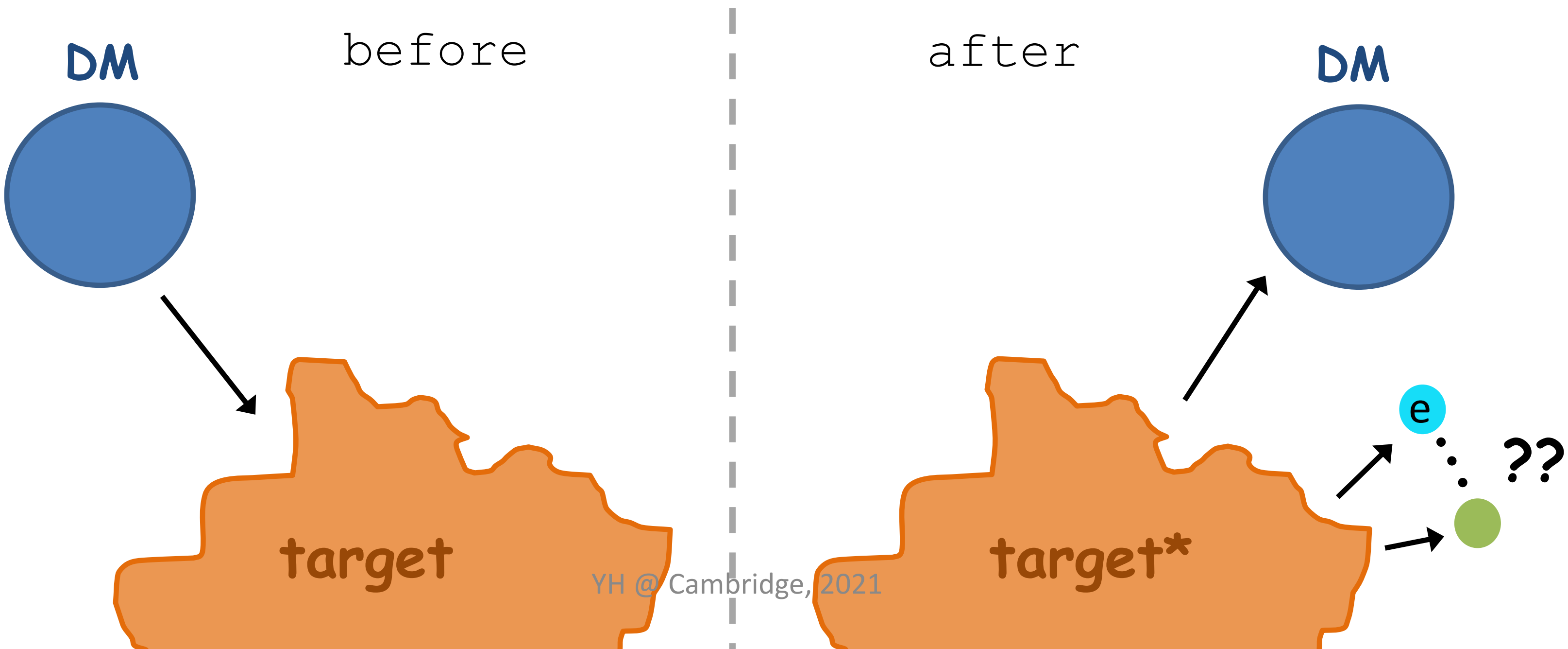
Detection Blueprints

Dark matter particle comes in

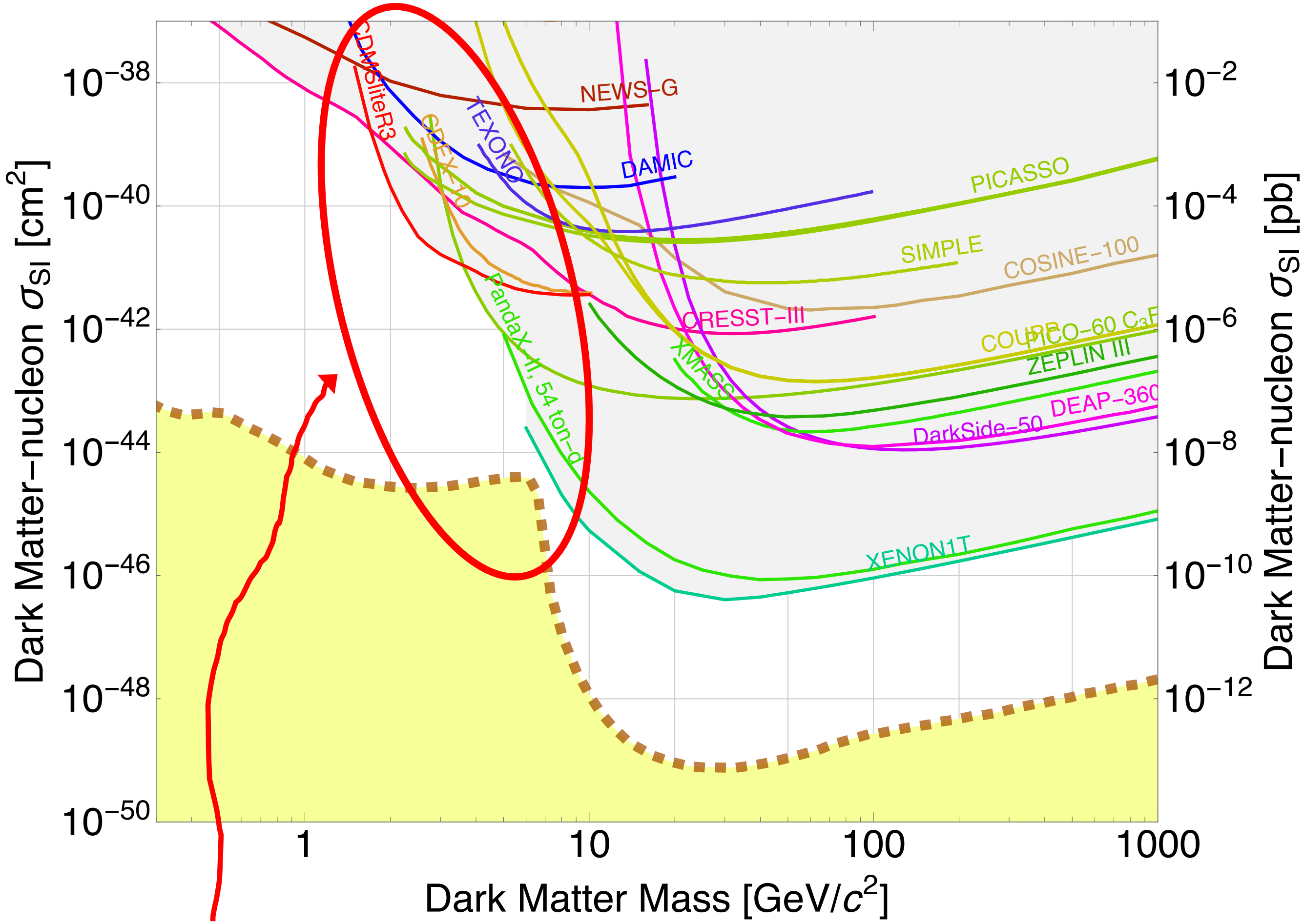
Hits a target in the lab

System reacts

Measure the reaction



Direct Detection

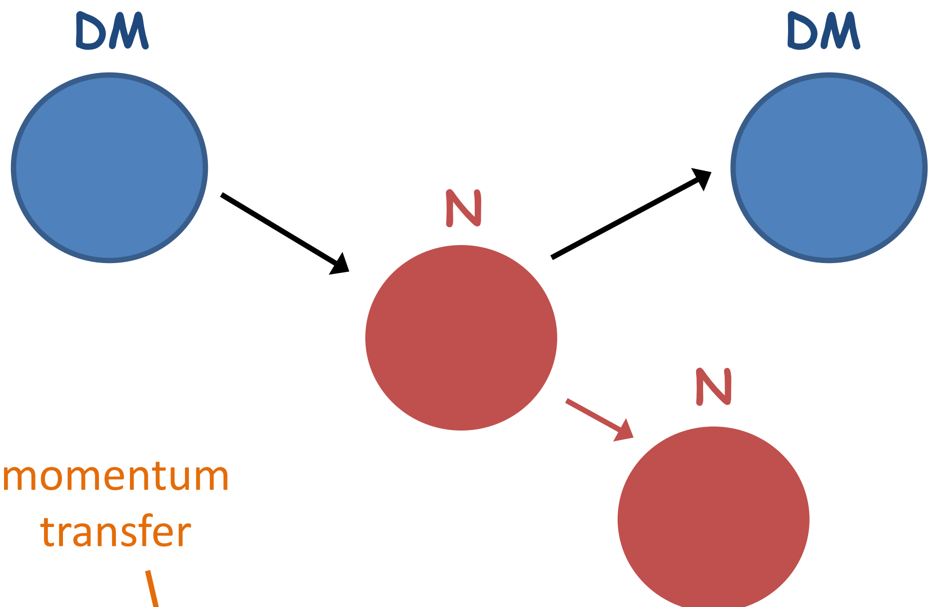


What's going on?

[*website:* supercdms.slac.stanford.edu/dark-matter-limit-plotter]

Current Experiments

Looking for nuclear recoils:
think billiard balls

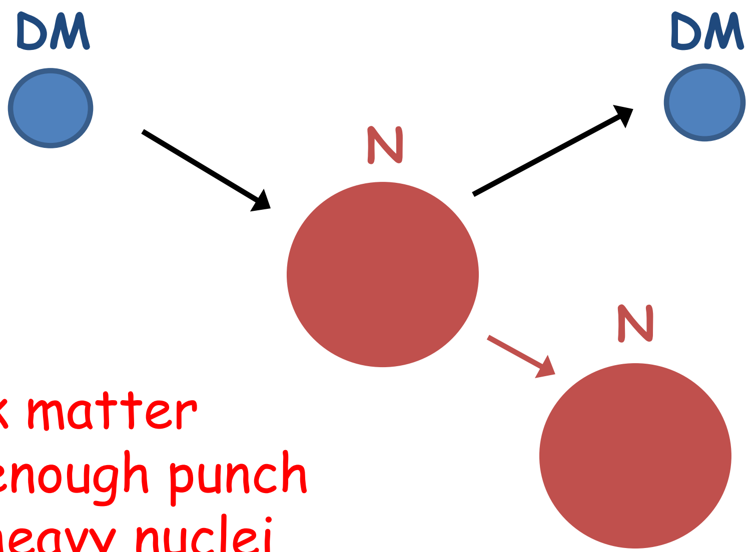


momentum transfer

$$E_{\rm NR} = \frac{q^2}{2m_N} = \frac{(m_{\rm DM}v)^2}{2m_N} \gtrsim E_{\rm threshold} \sim {\rm keV}$$

Current Experiments

Looking for nuclear recoils:
think billiard balls

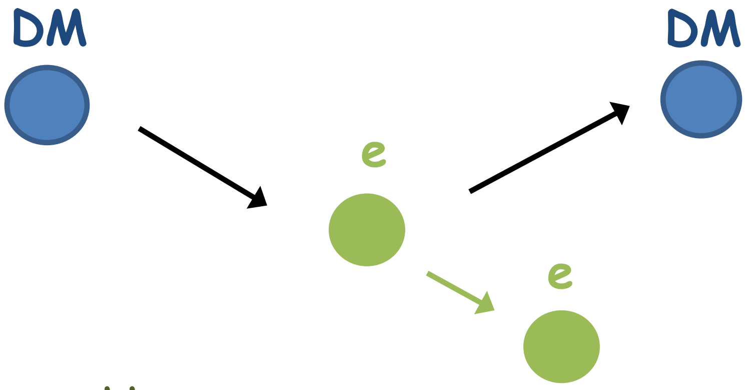


light dark matter
doesn't have enough punch
to kick the heavy nuclei

Lose sensitivity @ O(GeV) masses

New Avenues

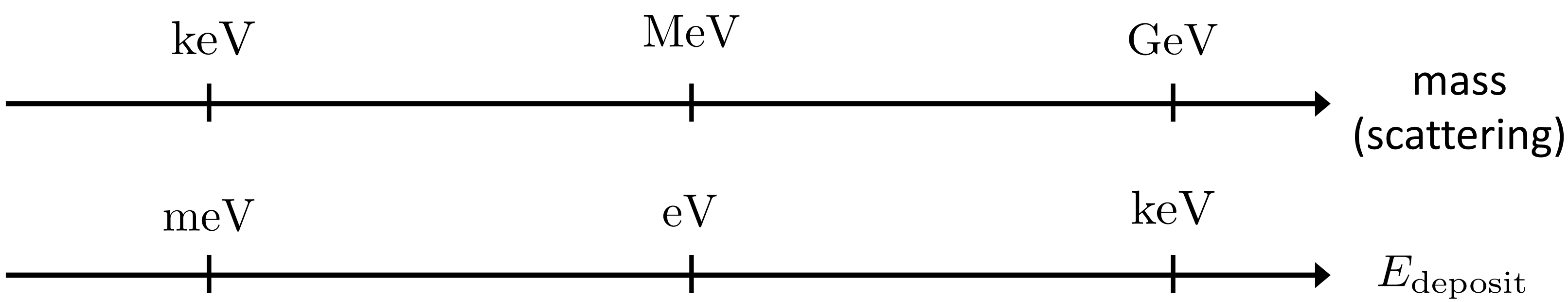
Light dark matter: scatter off electrons!

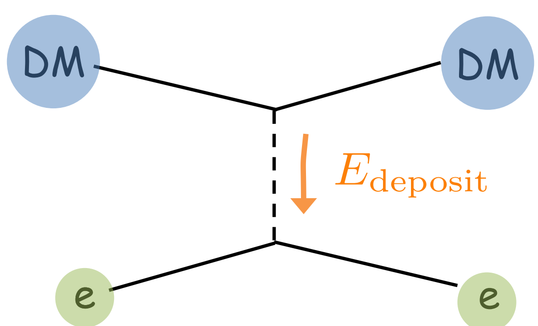


light dark matter
can give enough punch
to kick the light electrons

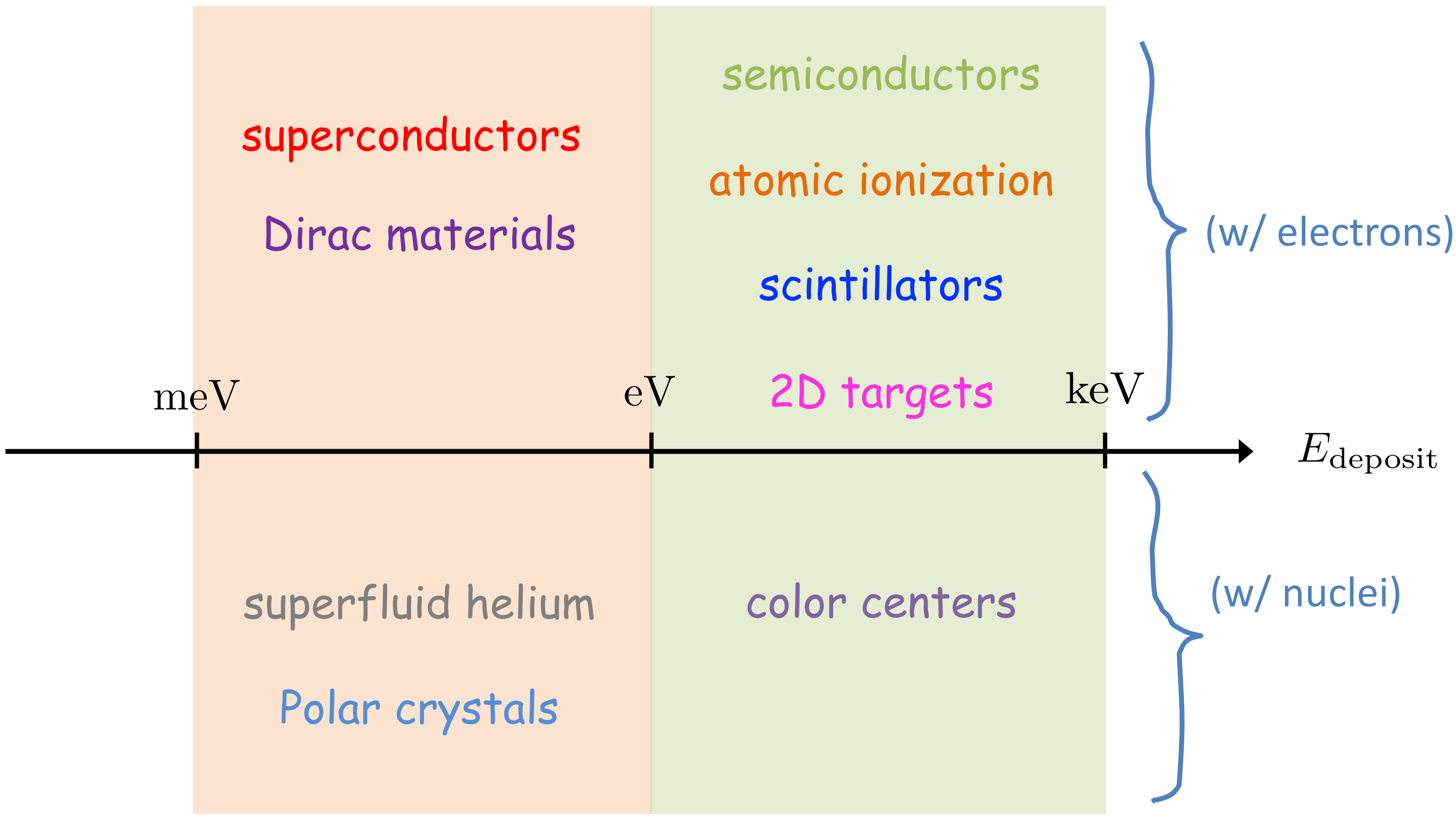
Energy guideline

Dark matter scattering: kinetic energy $m_{\rm DM} v^2 \sim 10^{-6} m_{\rm DM}$





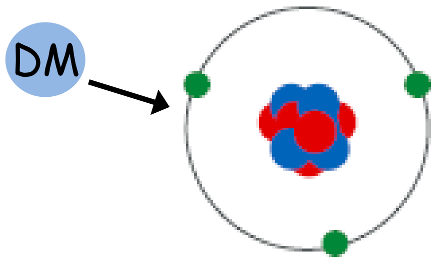
New proposals



Explosion of interest and ideas in recent times

Ex. #1: First ideas

Atomic ionization

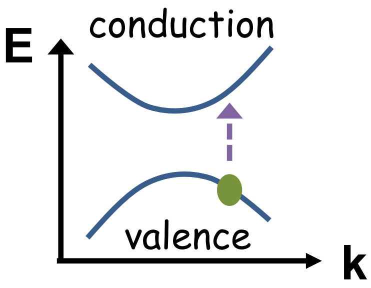


Xenon: ~12 eV

$$m_{\rm DM} \gtrsim 10 \text{ MeV}$$

[Essig, Mardon, Volansky, 2012]

Semiconductors



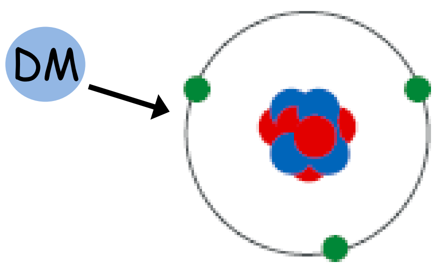
Ge, Si, Diamond, SiC: ~eV

$$m_{\rm DM} \gtrsim \text{MeV}$$

[Essig , Mardon, Volansky, 2012;
Graham, Kaplan, Rajendran, Walters, 2012;
Kurinsky, Yu, **YH**, Blas, 2019;
Griffin, **YH,** et al, 2020]

Ex. #1: First ideas

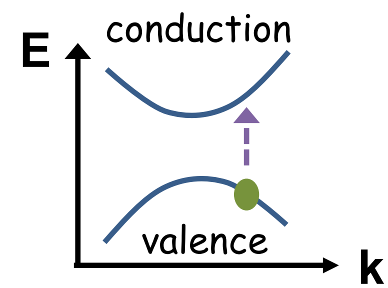
<u>Atomic ionization</u>



Xenon10/100/1T

$m_{\rm DM} \gtrsim 10\ {\rm MeV}$

<u>Semiconductors</u>



SuperCDMS, SENSEI

$m_{\rm DM} \gtrsim {\rm MeV}$

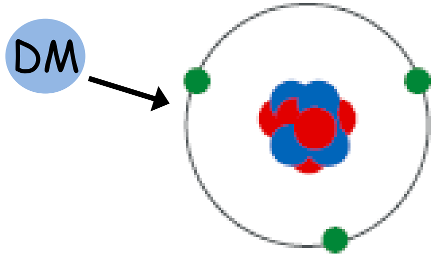
Are being experimentally realized

[Essig, Mardon, Volansky, 2012]
[Essig et al, 2012]
[Xenon100, 2016 & Xenon1T 2020]

[Essig , Mardon, Volansky, 2012;
Graham, Kaplan, Rajendran, Walters, 2012;
Kurinsky, Yu, **YH**, Blas, 2019;
Griffin, **YH**, et al, 2020]
[SuperCDMS 2020 & SENSEI 2020]

Ex. #1: First ideas

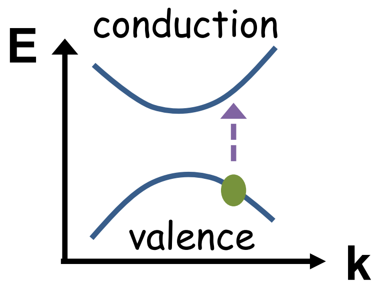
<u>Atomic ionization</u>



Xenon10/100/1T

$m_{\rm DM} \gtrsim 10$ MeV

<u>Semiconductors</u>



SuperCDMS, SENSEI

$m_{\rm DM} \gtrsim$ MeV

Smaller masses?

Ex. #2: Superconductors

- Ground state = Cooper pairs;
  Binding energy (gap) $\sim \mathrm{meV}$ ⟹ $m_{\mathrm{DM}} \sim \mathrm{keV}$
- The idea:
  DM scatters with Cooper pairs, deposits enough energy, breaks Cooper pairs → detect

Excitations

Excitation concentration philosophy	Sensor + target philosophy
[**YH**, Zhao, Zurek, PRL 2015; **YH**, Pyle, Zhao, Zurek, JHEP 2015]	[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

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Excitations

Excitation concentration philosophy

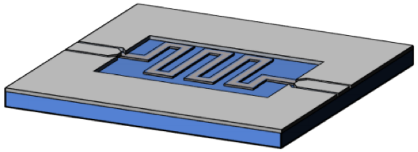
[**YH**, Zhao, Zurek, PRL 2015;
YH, Pyle, Zhao, Zurek, JHEP 2015]

Sensor + target philosophy

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

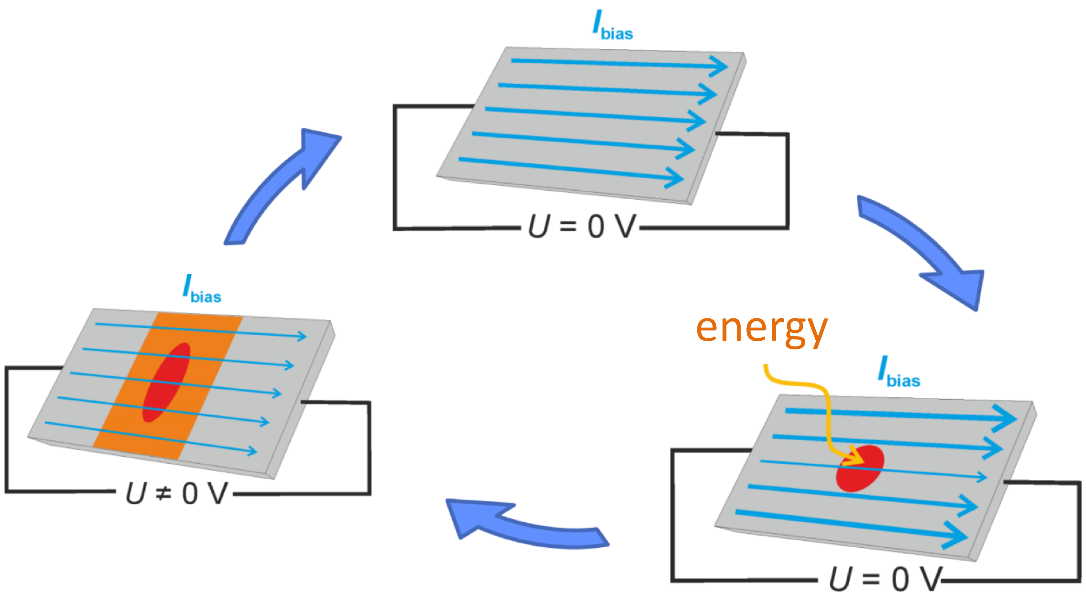
Ex. #2: Superconductors

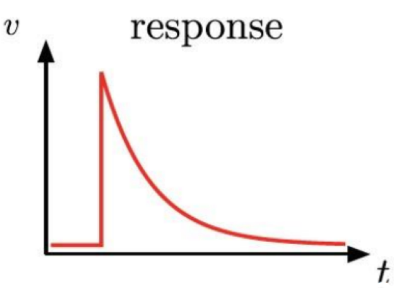
- Superconducting Nanowire Single Photon Detectors (SNSPDs)



Broadly used in quantum information science

- Ram an electron, create a hotspot, electrons diffuse away, resistive region across the nanowire → voltage pulse

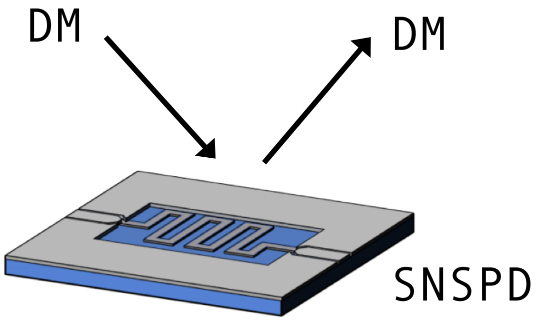




[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

Ex. #2: Superconductors

Use as simultaneous target + sensor (& multiplex)

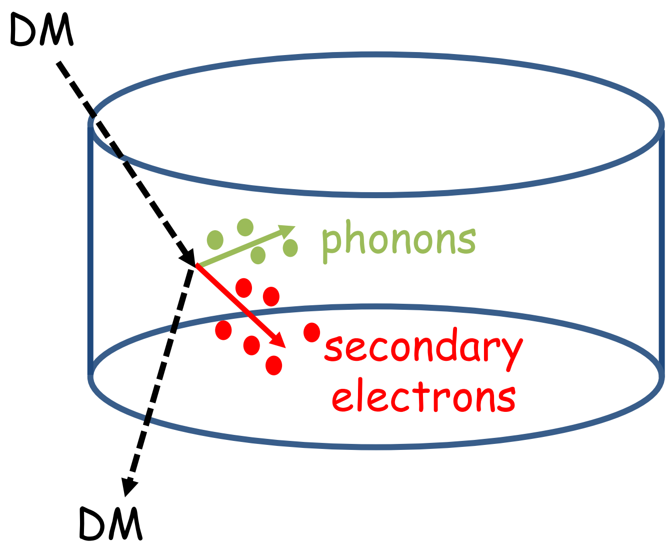


[Existing prototype]

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019]

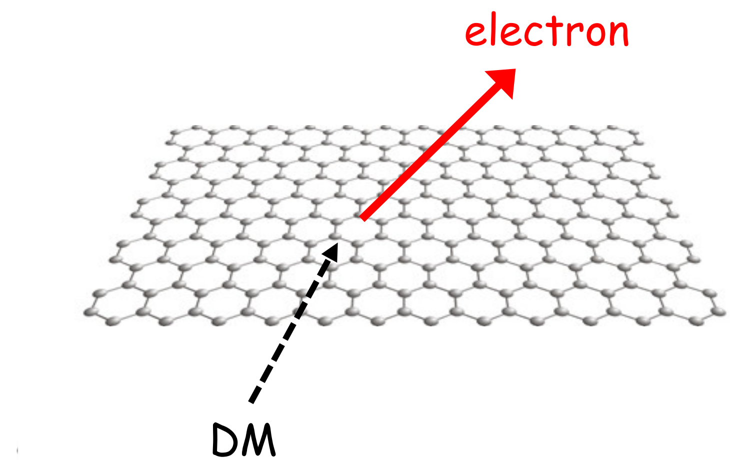
Directional Info?

Lose directional information
if detecting secondaries



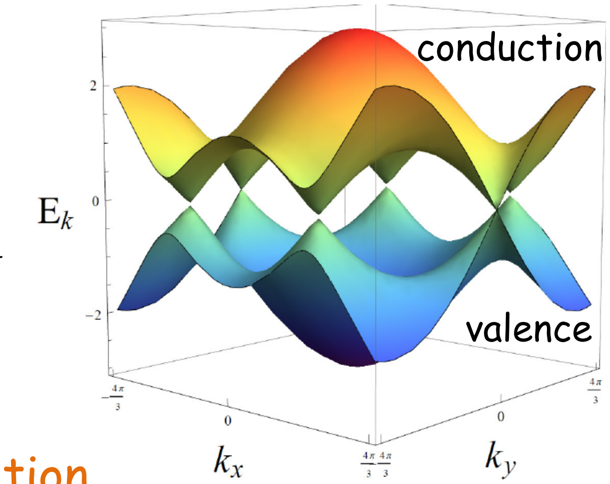
e.g. semiconductors,
bulk superconductors

Retain directional information
if observe primary!



2D targets;
graphene (& SNSPDs)

Ex. #3: Graphene



- 2D material with vanishing bandgap
- To eject electron: $E_{\rm eject} = E_b + \Phi \sim {\rm eV}$

Binding energy

Work function, O(eV)

⟹ **Sensitivity to m_{DM}~ MeV**

- <u>The idea:</u> DM scatters with valence electrons, deposits enough energy, ejects electron → detect

[**YH**, Kahn, Lisanti, Tully, Zurek, 2017]

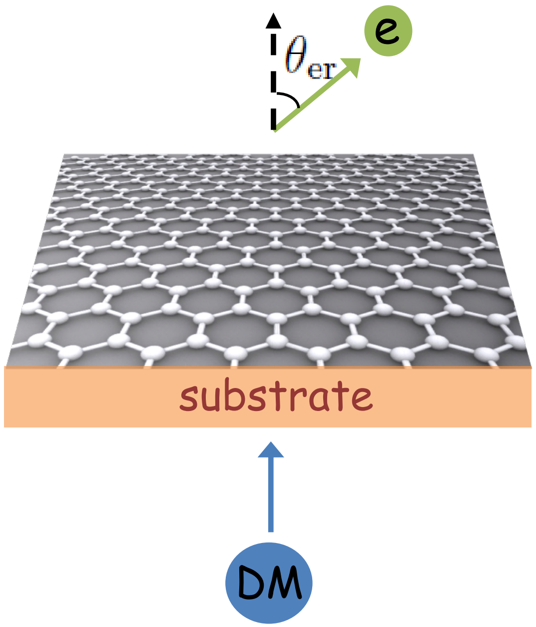
Ex. #3: Graphene

Electron follows incoming dark matter direction.

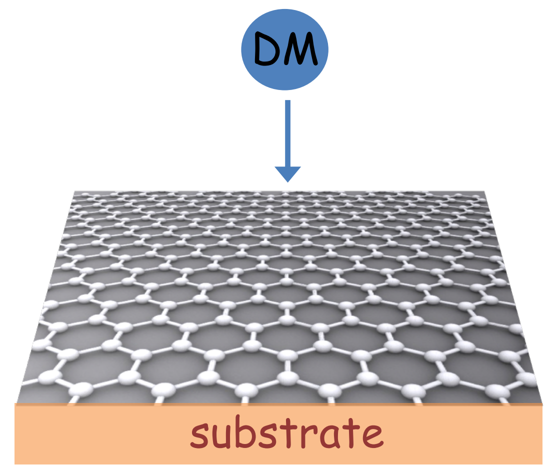
Naturally gives forward/backward discrimination

(separates signal from background)

Electron detected



electron not detected



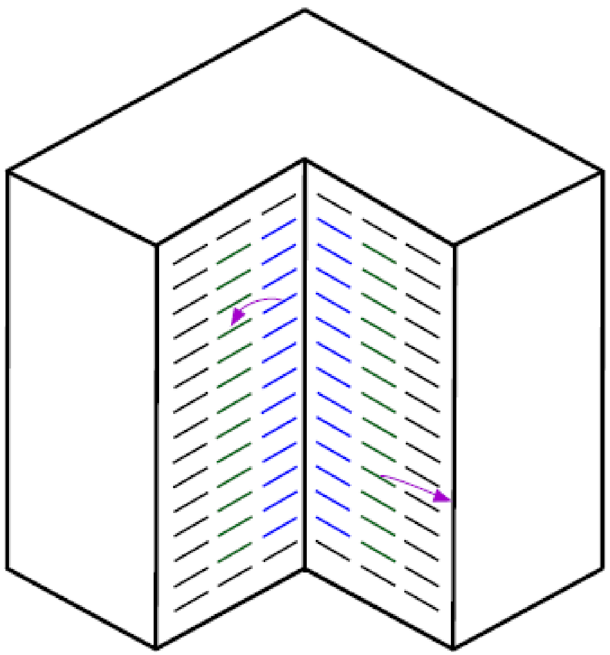
12 hours later

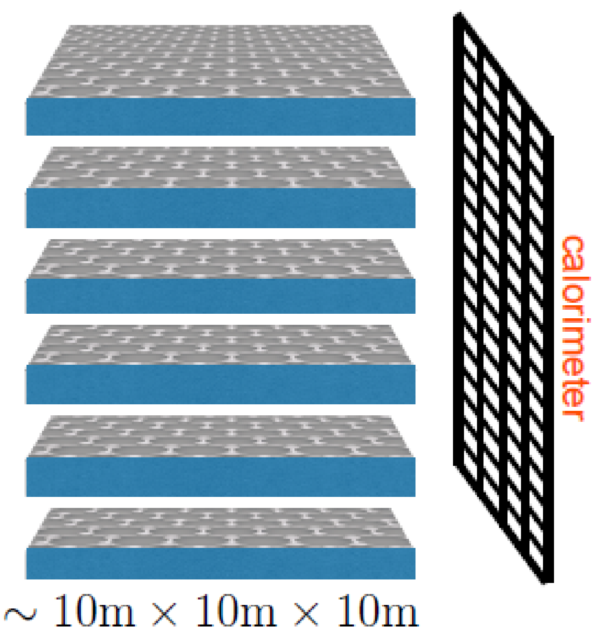
[**YH**, Kahn, Lisanti, Tully, Zurek, 2017]

Ex. #3: Design Concept

- ~0.5 kg graphene = area of Jerusalem old city = billions of cm^2 crystals

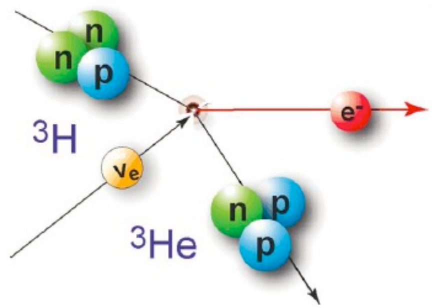
- Compact geometry: large mass via many stacks





Implement in PTOLEMY

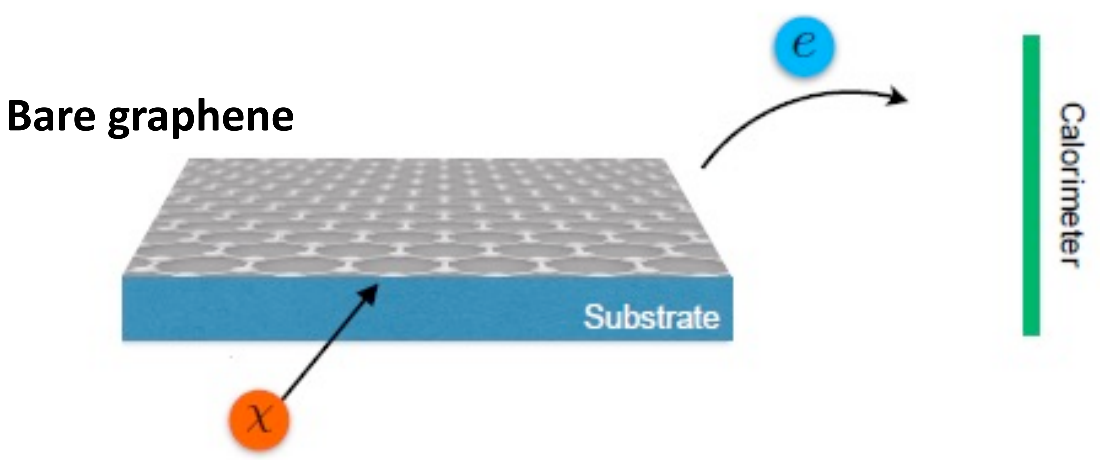
Experiment to detect relic neutrinos via capture on tritium.



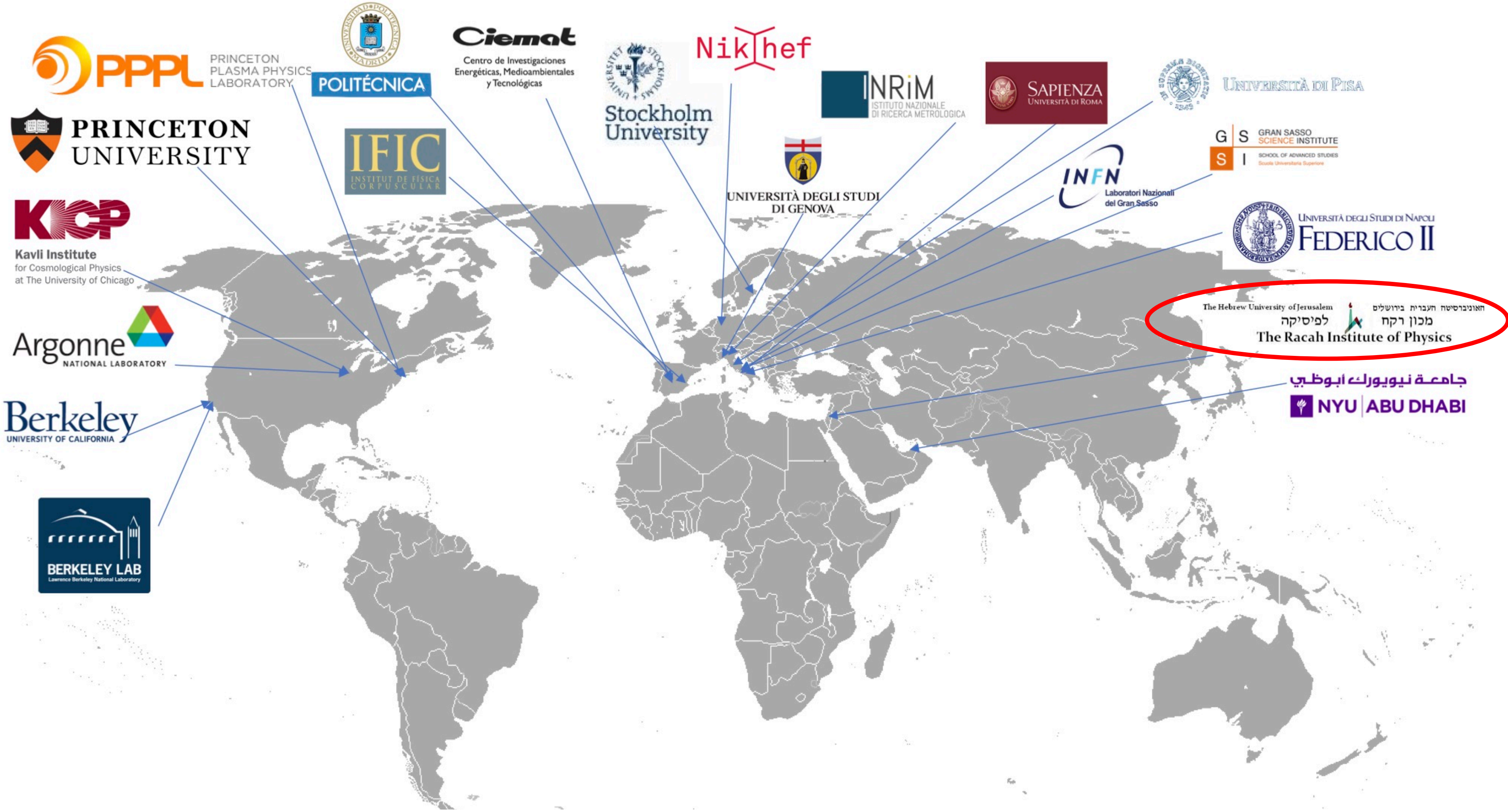
[Betts et al, 2013]

Will use tritiated graphene (~0.5 kg).

Borrow pure (un-tritiated) graphene for dark matter experiment!



PTOLEMY world map



PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

Compute Event Rate

[Events/unit time/unit mass]

$$\text{Rate} \propto \frac{1}{\rho_{\text{target}}} \times \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \times v_{\text{DM}} \times \text{target properties} \times \sigma_{\text{int}}$$

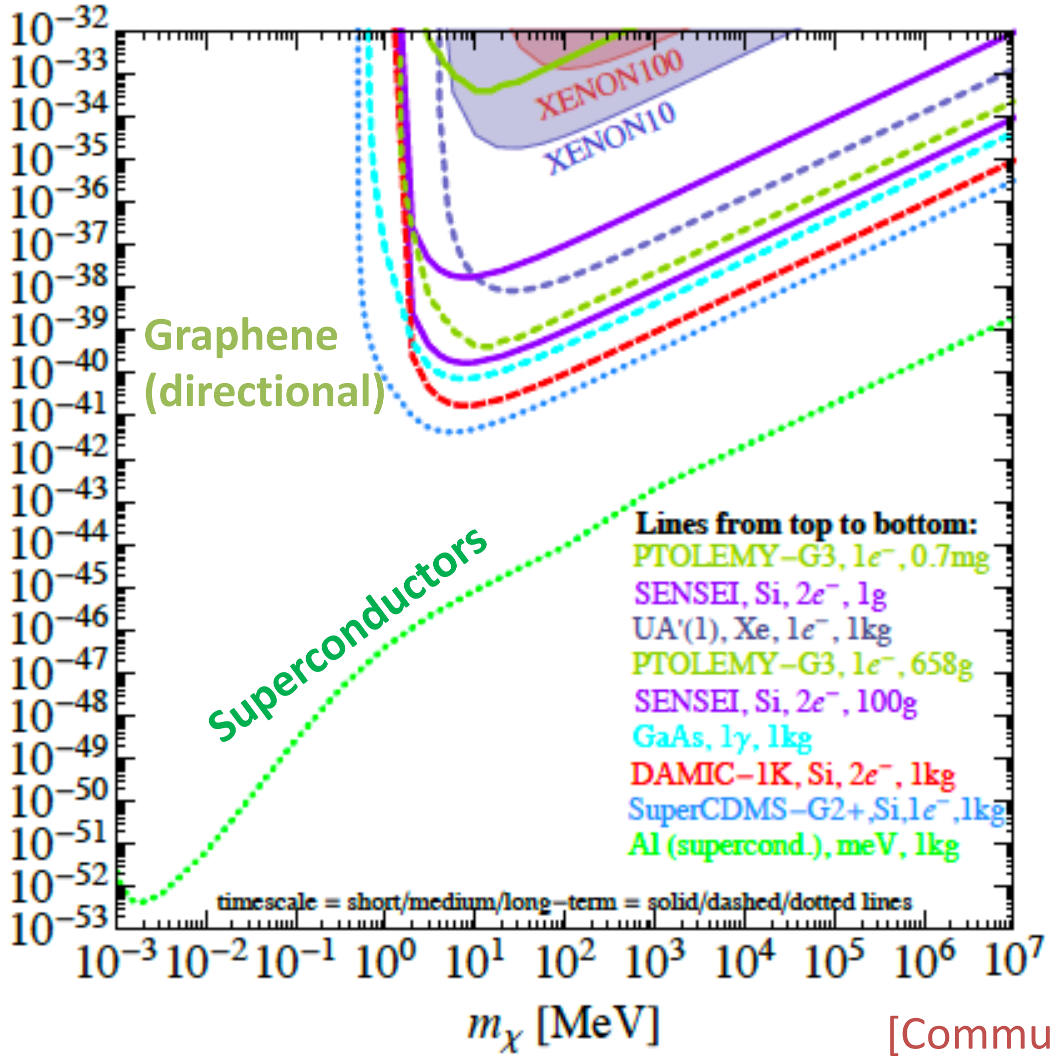
Target density

dark matter flux
(astrophysics)

condensed matter
physics

particle physics

Scattering Reach



DM-electron scattering xsec @ $q = \alpha m_e$ w/ light mediator

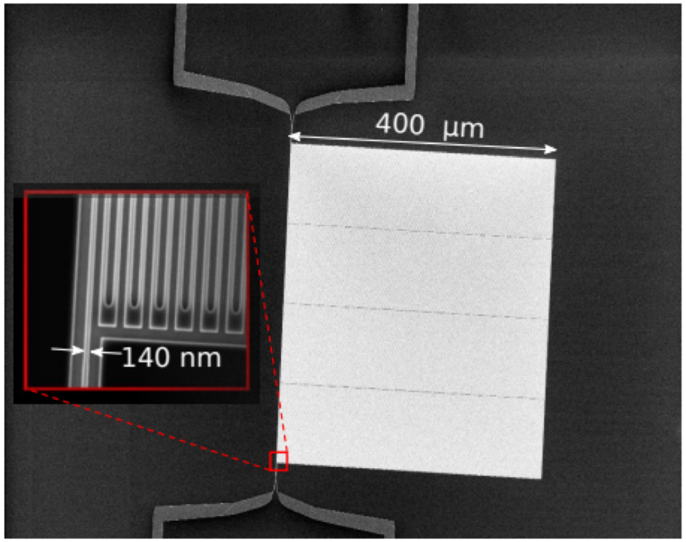
[a few events in kg-year exposure]

Amazing reach!

[Community report, 2017]

Existing Prototype Device

WSi SNSPD, 4.3 nanogram, 0.8 eV threshold,
no dark counts in 10000 seconds (~3 hours)

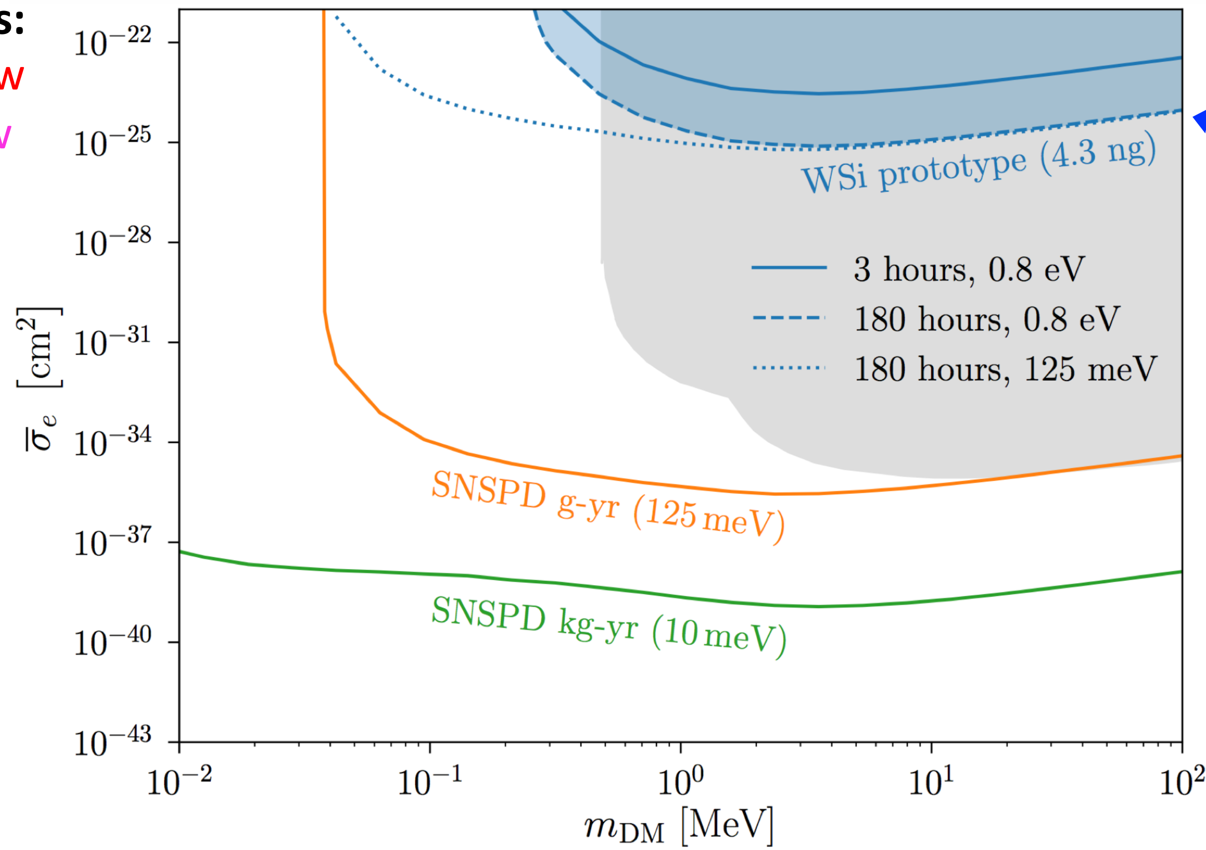


By now have 180 hours with 4 dark counts

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + to appear (w/ Lehmann)]

Scattering Reach

Colored curves:
Large array, low threshold, low dark count SNSPDs



New bound (Preliminary)

DM-electron scattering xsec @ $q = \alpha m_e$ w/ light mediator

[**YH**, Charaev, Nam, Verma, Colangelo, Berggren, PRL 2019 + to appear (w/ Lehmann)]

Pushing Thresholds Lower

Single-photon detection in the mid-infrared up to 10 micron wavelength using tungsten silicide superconducting nanowire detectors

V. B. Verma,[1, a)] B. Korzh,[2, b)] A. B. Walter,[2] A. E. Lita,[1] R. M. Briggs,[2] M. Colangelo,[3] Y. Zhai,[1] E. E. Wollman,[2] A. D. Beyer,[2] J. P. Allmaras,[2] B. Bumble,[2] H. Vora,[1] D. Zhu,[3] E. Schmidt,[2] K. K. Berggren,[3] R. P. Mirin,[1] S. W. Nam,[1] and M. D. Shaw[2]

[1)] *National Institute of Standards and Technology, Boulder, CO, USA.*

[2)] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, USA*

[3)] *Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, USA.*

(Dated: 21 December 2020)

We developed superconducting nanowire single-photon detectors (SNSPDs) based on tungsten silicide (WSi) that show saturated internal detection efficiency up to a wavelength of 10 μm. These detectors are promising for applications in the mid-infrared requiring ultra-high gain stability, low dark counts, and high efficiency such as chemical sensing, LIDAR, dark matter searches and exoplanet spectroscopy.

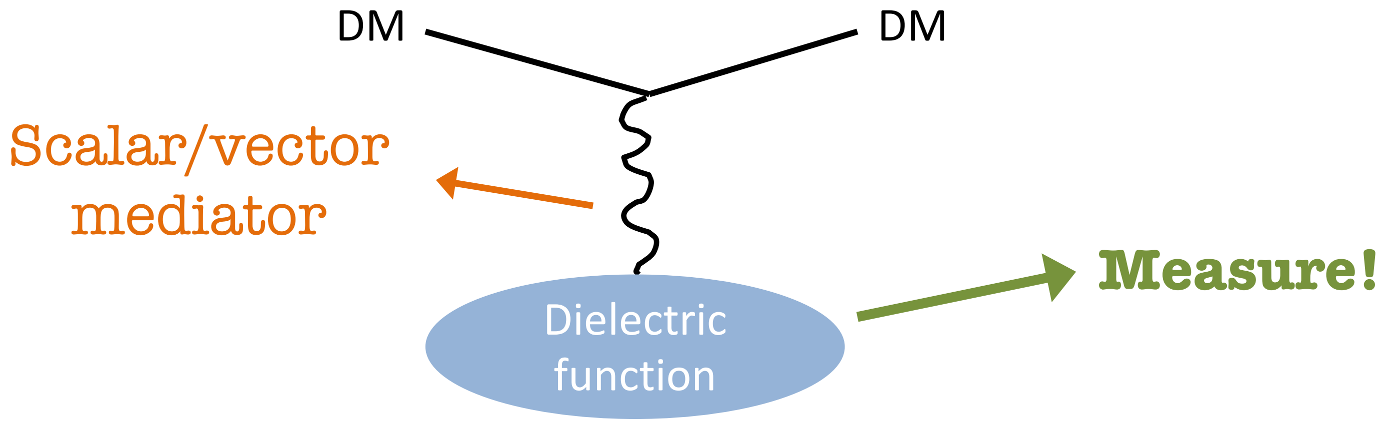
Demonstrated WSi SNSPDs w/ 125meV energy threshold

[arXiv:2012.09979]

New Formalism

DM-electron scattering in any material
is determined by the dielectric function.

For any DM interaction that couples to electron density

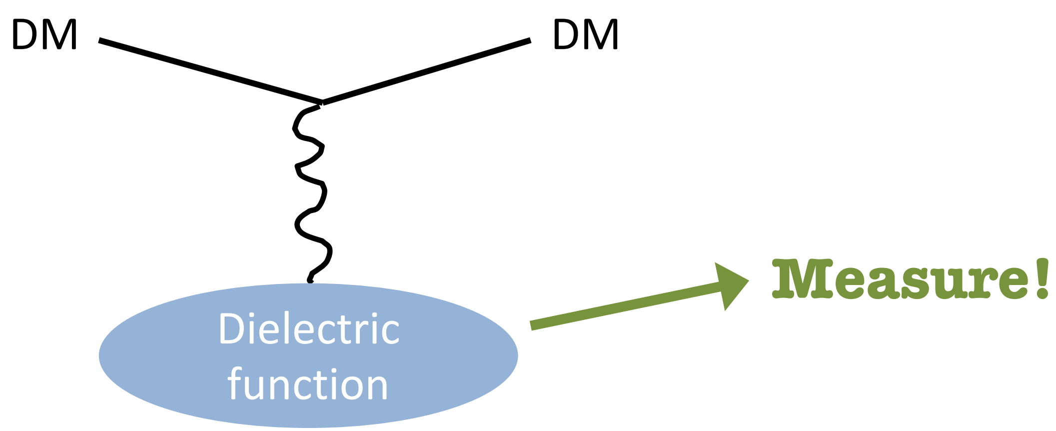


[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

New Formalism

Automatically includes many-body effects of the material

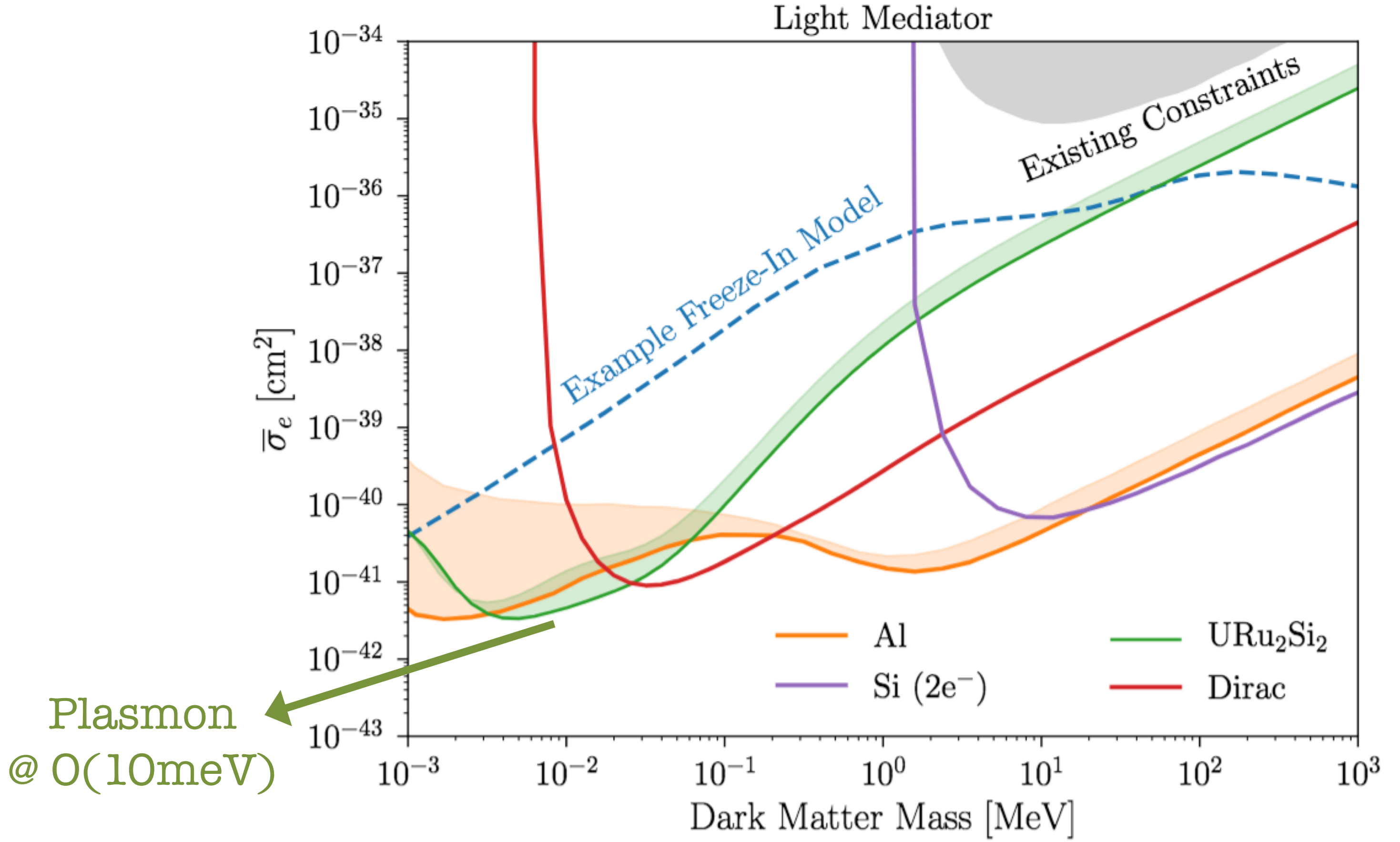
Collective modes (e.g. plasmon),
not just single particle excitations



Identify promising materials for DM detection

[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

E.g. Heavy Fermions



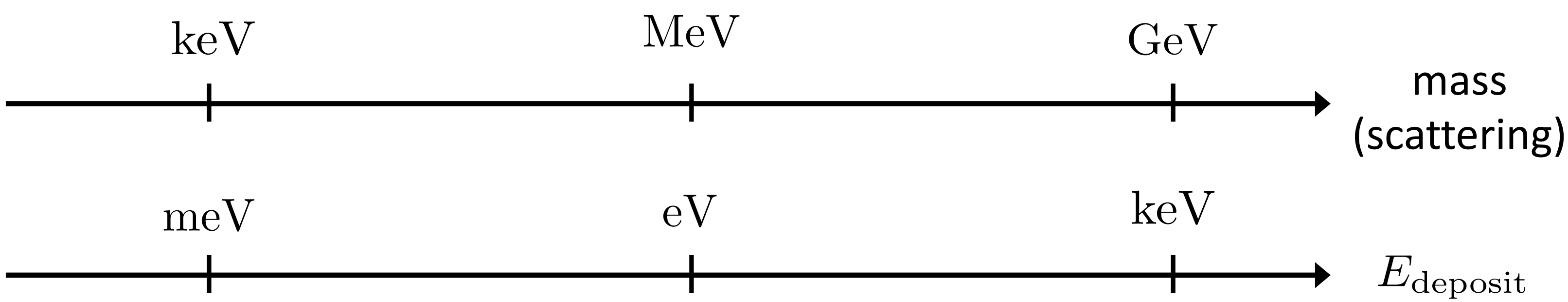
Identify promising materials for DM detection

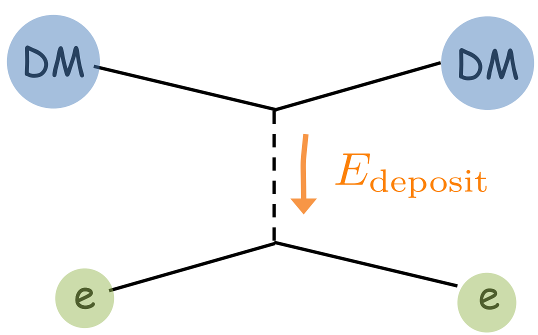
[**YH**, Kahn, Kurinsky, Lehmann, Yu, Berggren, arXiv:2101.08263]

Any given target material can go even further.

Absorption vs. Scattering

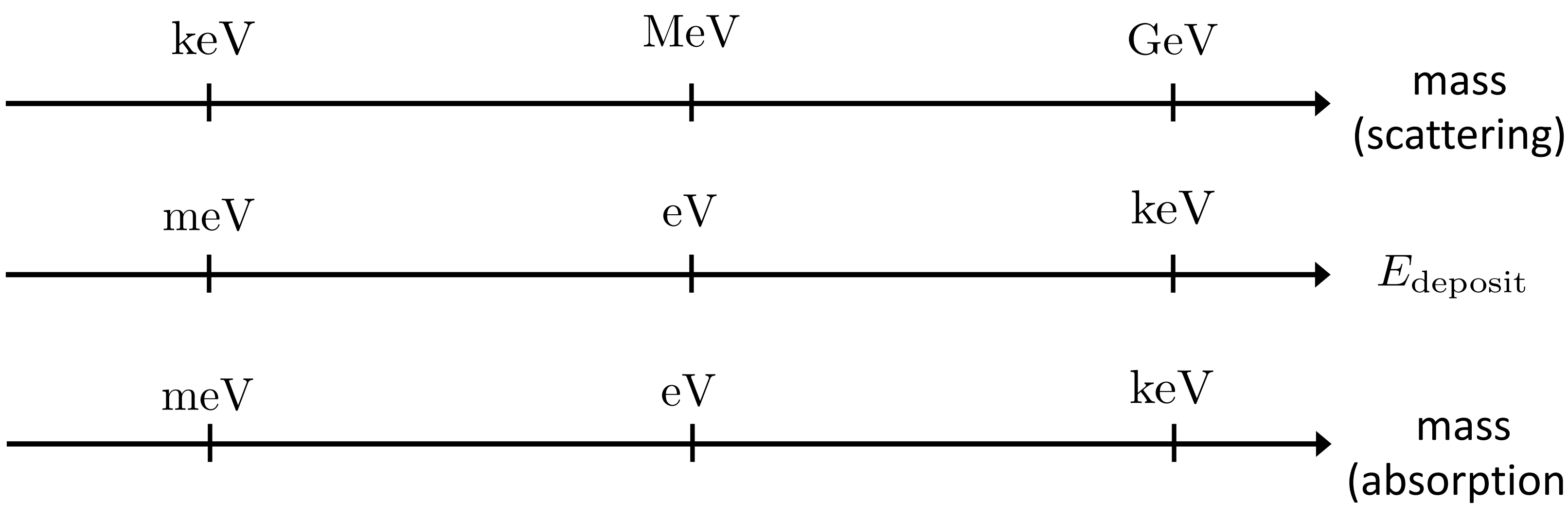
Dark matter scattering: kinetic energy $m_{\mathrm{DM}} v^2 \sim 10^{-6} m_{\mathrm{DM}}$

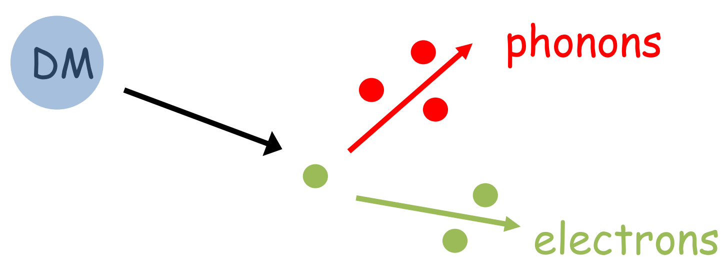




Absorption vs. Scattering

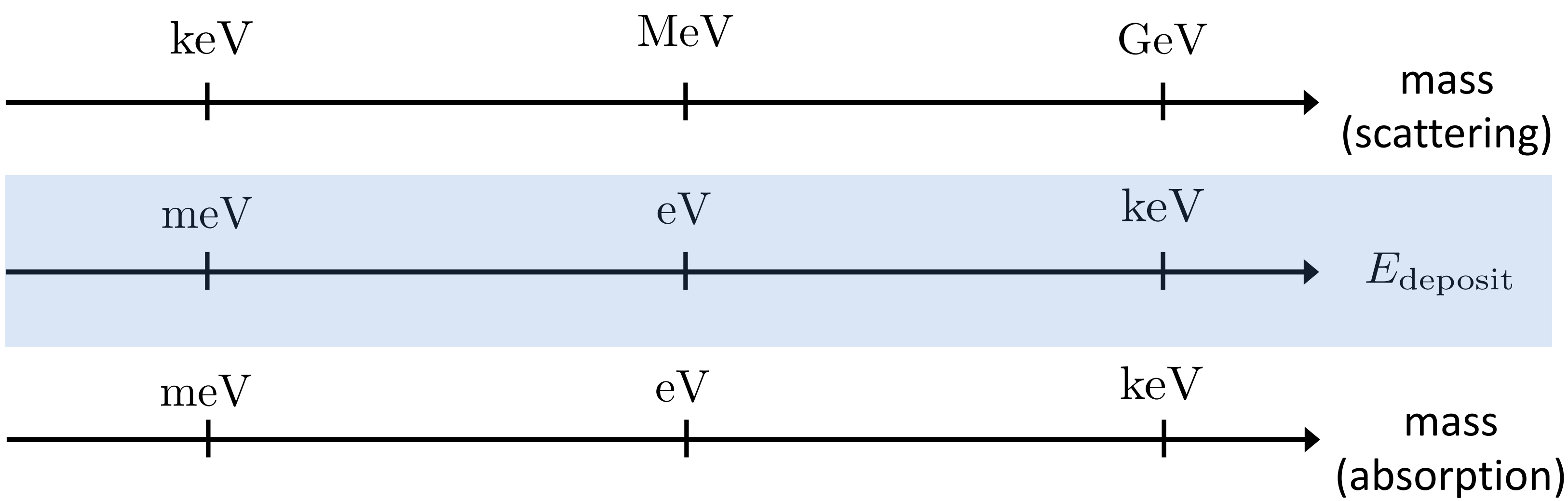
Dark matter absorption: all the mass-energy $m_{\rm DM}$





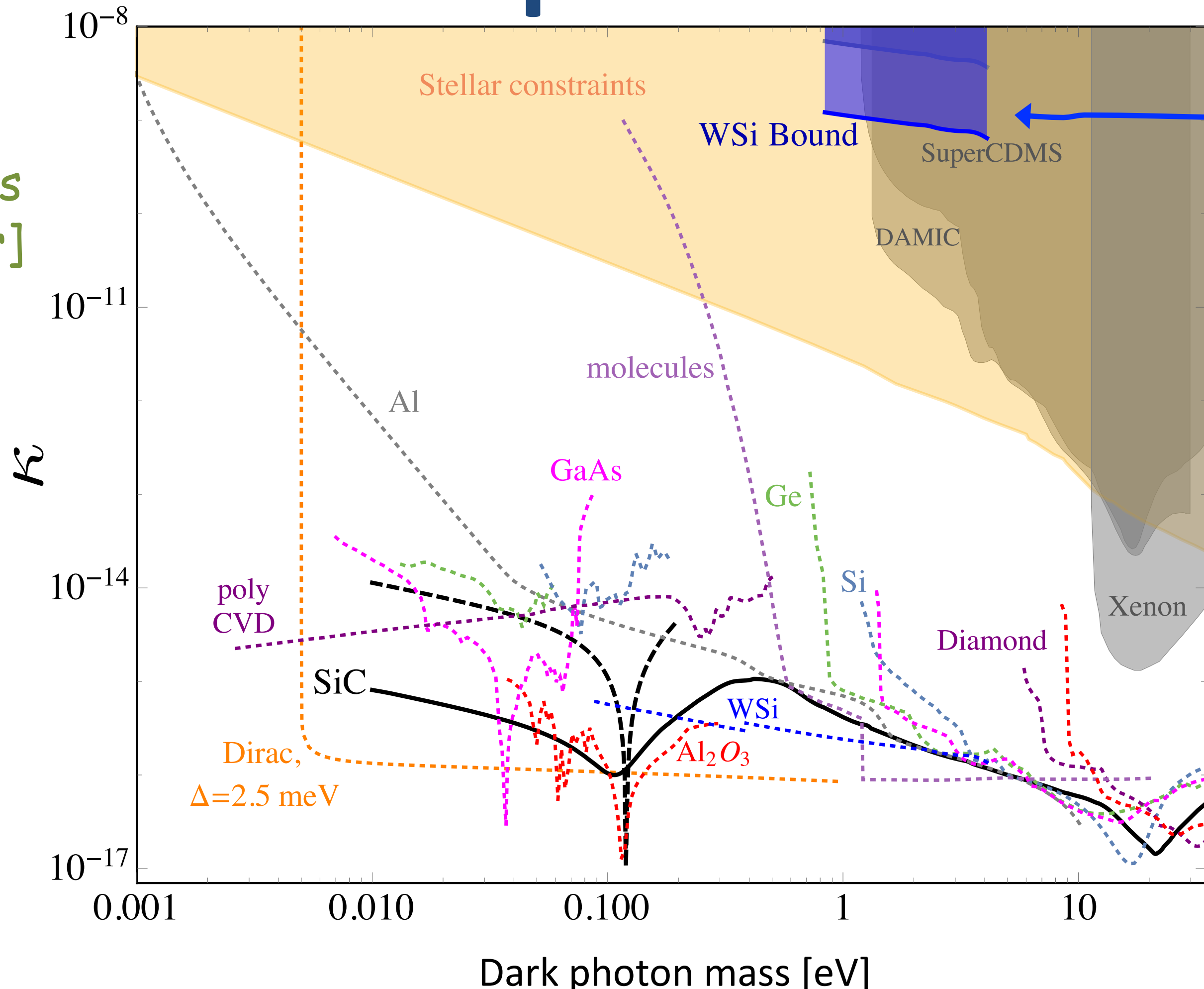
Absorption vs. Scattering

Two (mass ranges) for the price of one :-)



Absorption Reach

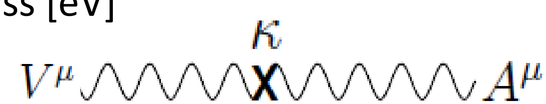
[projections for kg-year]



New prelim' bound:
WSi SNSPD prototype 4.3ng in 180 hours

[Kurinsky, Yu, **YH,** Blas, PRD 2019; **YH** et al, PRL 2019; Griffin, **YH**, et al, 2020]

Kinetically mixed dark photon

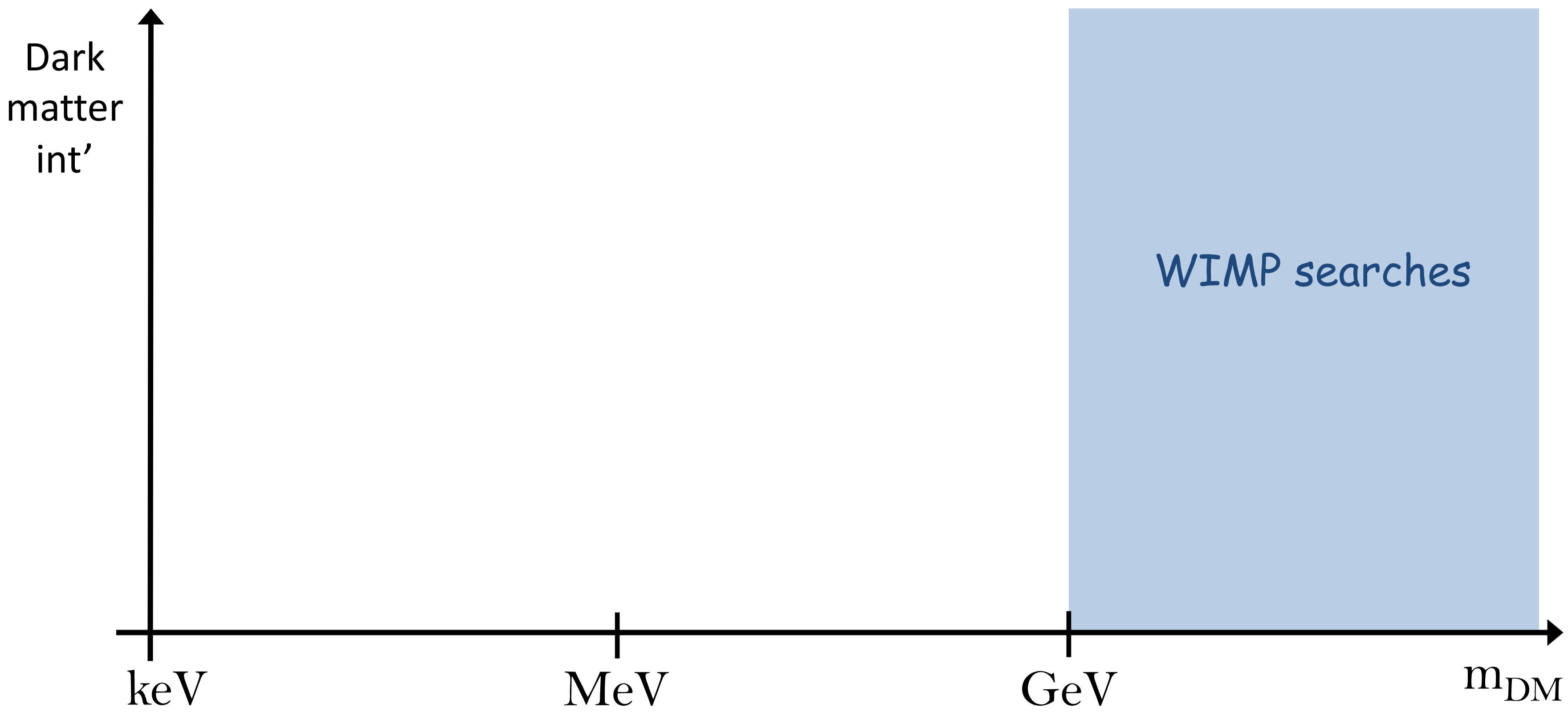


Take aways

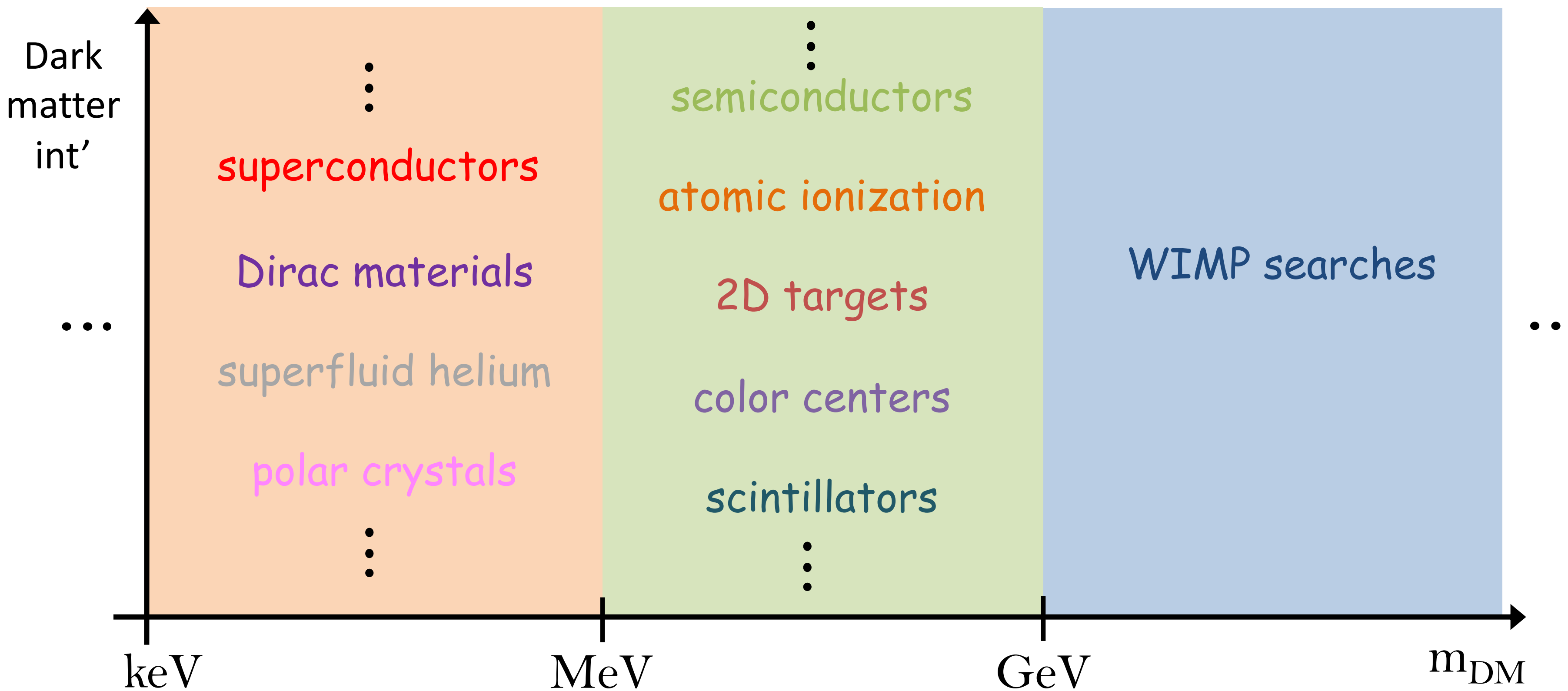
Outlook

- Lots of activity for light dark matter
- Theory ←→ experiment
- By no means exhausted…
- It’s ok for an idea to seem crazy at first
- The best ideas might still be ahead

Prospects

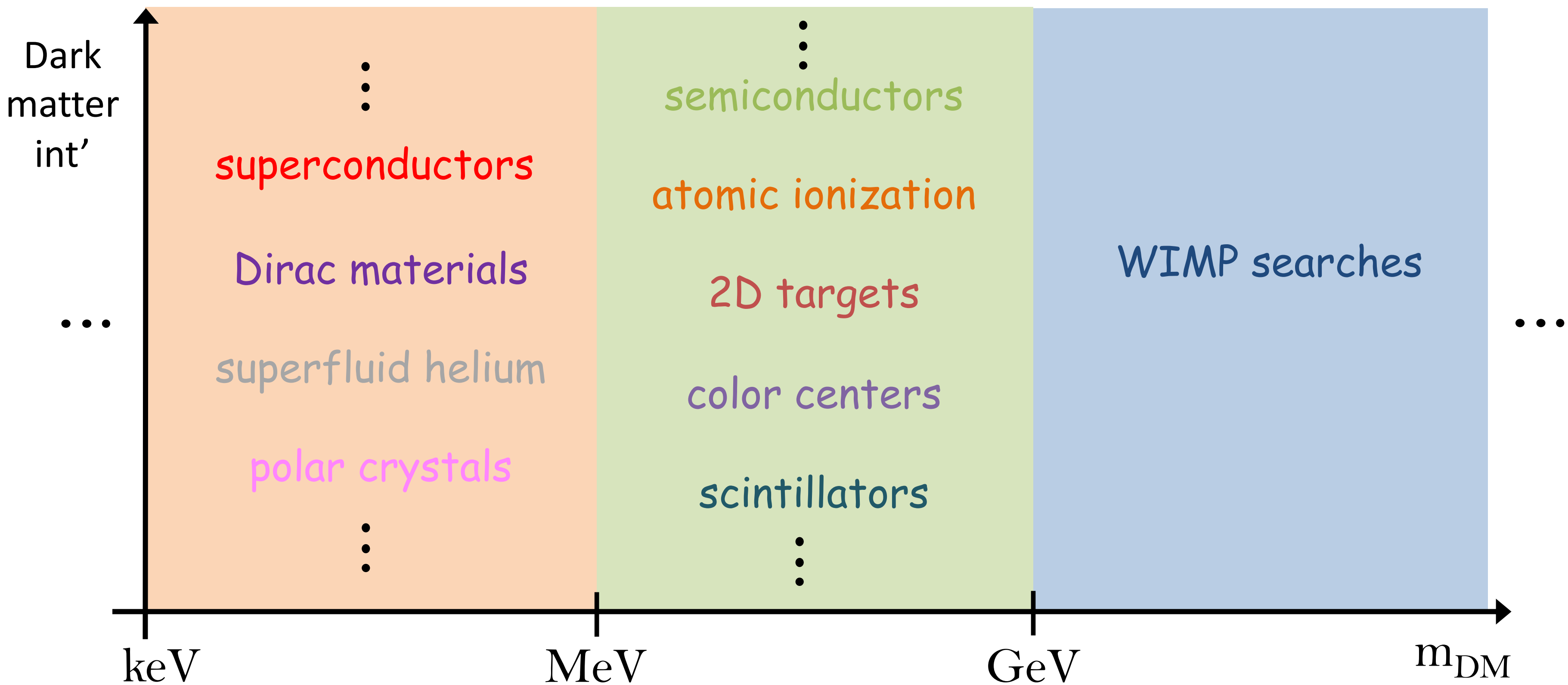


Prospects



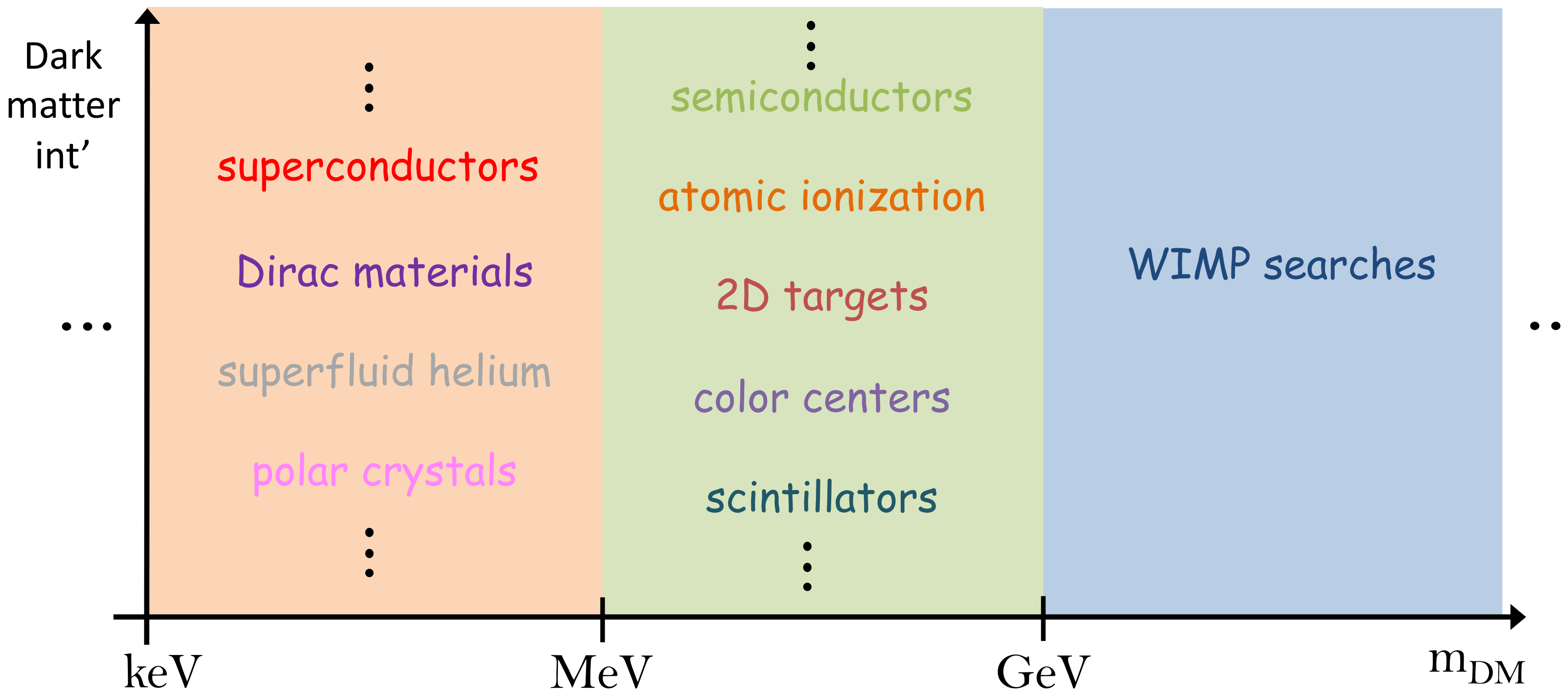
Burgeoning field in recent years

Prospects



Experimentalists are going after these ideas now!

Prospects



Interface particle physics/condensed matter physics/ quantum information science/precision measurements

If you have any (crazy) new ideas,
please be in touch :-)

Thanks!